Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science

Bente Bjerkan

Stair Descent Kinematics and Leg Strength in People with Knee Osteoarthritis

A Cross-Sectional Study

Master's thesis in Human Movement Science
Supervisor: Karin Roeleveld
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ABSTRACT

Background: Difficulties descending stairs is commonly reported in people with knee osteoarthritis (OA). Further, strength deficits in leg muscles have been identified in this population.

Objectives: The aims of this thesis were 1) to examine differences in stair descent kinematics and leg strength between people with knee OA and healthy controls, 2) to gain insight into the contribution of leg strength to variance in joint angles during stair descent in people with knee OA, and 3) to explore whether there is an association between self-reported difficulties and kinematics during stair descent in people with knee OA.

Material and methods: The study has a cross-sectional design, comparing 28 knee OA cases (age 61.7 ± 6.4 years) to 31 healthy controls (age 55.3 ± 8.0 years). The subjects performed a stair task, which was recorded using eight cameras (Oqus Capture system) and analysed in Visual3D. Concentric and eccentric knee strength was measured at 60°/ sec. using a Biodex dynamometer. Isometric hip abduction was measured using a hand-held dynamometer placed under a fixation belt. All strength measures were normalised to body weight. Self-reported difficulties descending stairs were derived from the KOOS questionnaire (item A1).

Main Results: Compared to healthy controls, knee OA cases had longer total stance phases (≈ +0.2 sec., $p< 0.001$), and they spent relatively more time in double support. Further, they displayed smaller knee flexion angles (-7.2°, $p< 0.001$) and larger hip adduction angles (+4.5°, $p= 0.005$) in their supporting leg at contralateral toe-down, when their most affected leg was compared to healthy controls. Group differences were still present after adjusting for leg length and single stance duration. Knee OA cases were generally weaker, especially in their most affected leg. (Unadjusted) eccentric quadriceps strength was particularly reduced (-0.84 N/kg, $p< 0.001$). Leg strength did not explain variance in knee- or hip angles within the OA group. Self-reported difficulties descending stairs were weakly correlated with relative time spent in double support (Spearman's Rho 0.335, $p= 0.010$), but no clear associations could be found with other kinematic variables.

Conclusion: People with knee OA display altered kinematics during stair descent and reduced leg strength compared to healthy controls. Leg strength does not seem to explain variance in knee- or hip angles in this population. There is no clear association between self-reported difficulties descending stairs and joint angles.

SAMMENDRAG

Bakgrunn: Problemer med å gå ned trapper rapporteres hyppig blant personer med kneartrose. Det er tidligere funnet redusert styrke i benmuskulatur i denne populasjonen.
Hensikt: Målsettingene for denne oppgaven var 1) å studere forskjeller i kinematikk under nedovergange i trapp, samt forskjeller i benstyrke, mellom personer med kneartrose og friske kontroller, 2) å få innsikt i om benstyrke bidrar til variasjon i leddvinkler under nedovergange i trapp hos personer med kneartrose, og 3) å finne ut om det er noen sammenheng mellom selvrapporterte vanskeligheter og kinematiske variabler under nedovergange i trapp.
Materiale og metode: Dette er en tverrsnittstudie som sammenlikner 28 personer med kneartrose (alder 61.7 ± 6.4 år) med 31 friske kontroller (alder 55.3 ± 8.0 år). Deltakerne utførte en trappetest, som ble filmet med åtte kameraer (Oqus Capture system) og analysert i Visual3D. Konsentrisk og eksentrisk knestyrke ble målt ved bruk av et Biodex dynamometer (60°/ sec). Isometrisk hofteabduksjon ble målt med et håndholdt dynamometer plassert under et fiksasjonsbelte. Alle styrkemål ble normalisert for kroppsvekt. Spørreskjemaet KOOS (item A1) ble brukt for å registrere selvrapporterte vanskeligheter med å gå ned trapper.
Hovedfunn: Sammenliknet med friske kontroller, hadde personene med kneartrose lengre standfaser (≈ +0.2 sek., $p< 0.001$), og de brukte relativt mer tid i dobbel standfase. Videre hadde de mindre knefleksjon (-7.2°, $p< 0.001$) og mer hofteadduksjon (+4.5°, $p= 0.005$) i standbenet ved slutten av singel standfase, når det mest affiserte benet ble sammenliknet med friske kontroller. Gruppeforskjellene var fremdeles fremtredende etter å ha justert for benlengde og varighet av singel standfase. Kneartrosegruppen var generelt svakere, spesielt i det mest affiserte benet. (Ujustert) eksentrisk quadricepsstyrke var særlig redusert (-0.84 N/kg, $p< 0.001$). Benstyrke forklarte ikke varians i kne- eller hoftevinkler i kneartrosegruppen. Selvrapporterte vanskeligheter med å gå nedover trapp viste en svak korrelasjon med relativ tid brukt i dobbel standfase (Spearman's Rho 0.335, $p= 0.010$), men ingen tydelig sammenheng med andre kinematiske variabler.
Konklusjon: Personer med kneartrose har endret kinematikk under trappegange og redusert benstyrke sammenliknet med friske kontroller. Benstyrke ser ikke ut til å forklare varians i kne- eller hoftevinkler i denne pasientgruppen. Det er ingen klar sammenheng mellom selvrapporterte vanskeligheter og leddvinkler under trappegange.

ACKNOWLEDGEMENTS

The current study is part of the FUNKART project (INB, NTNU), which aims to explore mechanisms explaining physical function in patients with knee OA. This thesis could not have been accomplished without the help and support of a few people, who deserve to be mentioned and thanked:

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INTRODUCTION

Osteoarthritis (OA) is a chronic condition which has traditionally been regarded as a cartilage disease. Based on current knowledge, it is now considered to be a whole-organ disease with various degrees of symptoms and structural signs (1). Pain and loss of function are main clinical features, and activities of daily life may be affected (1, 2). Joint effusion, bony swelling and crepitation may also be present, and in advanced stages of the disease, structural deformities may occur (2). Several classification systems for diagnosing OA have been developed. Radiographically, OA is typically classified based on the degree of osteophyte formation, joint-space narrowing and bone sclerosis (2). The Kellgren-Lawrence (KL) scale is often used for this purpose, with grades ranging from 0 (no radiographic OA present) to 4 (severe radiographic OA) (3). In the knee joint, OA may affect the tibiofemoral joint (medial, lateral or both compartments), as well as the patellofemoral joint (4). Although structural changes within the joints are common, there is often a discrepancy between x-ray findings and clinical symptoms (1, 5). This has led to the development of several clinical classification criteria, used alone, or in combination with radiographic or laboratory findings (4).

The prevalence of OA is dependent on location of the disease and definition (radiographic vs. symptomatic) (2). According to the Global Burden of Disease (GBD) study of 2010, the knee joint is the most commonly affected site with an estimated global age standardized prevalence of 3.8% (5). The researchers did, however, note that the true prevalence might have been substantially underestimated due to a strict definition of OA (both symptomatic and radiographic OA had to be present, and people with KL grade 1 were excluded). The prevalence increases with age, and it is slightly higher in females than in males. In a Swedish cohort aged 56-84, radiographic knee OA was reported to be 25.6% in men and 26.4% in women. Symptomatic knee OA, on the other hand, was 10.5% and 11.0% for men and women, respectively (6). In addition to age and female gender, obesity and previous injury are known risk factors for knee OA (7). With increasing incidence, this disease has a high impact worldwide and is one of the leading causes of global disability (5, 7).

Difficulties walking stairs is commonly reported in this population, and *descending* stairs is often mentioned as particularly challenging (based on personal clinical experience from patient consultations). Several studies have found that people with knee OA descend stairs more slowly than healthy controls (8-11). It has been suggested that individuals with knee OA may attempt to minimize pain by reducing the moments acting on the knee (8). Different compensatory mechanisms may be used to achieve this. One such strategy could be to decrease knee flexion during weight-bearing. Studies investigating sagittal plane knee movements during stair descend, have found reduced knee flexion angles at various time points during stair descent in knee OA cases compared to healthy controls (8, 9, 12-14). There is also evidence of increased pelvic range of motion during stair descent in people with knee OA (15), which could also reflect a compensatory strategy. The same study found an inverse association between leg extension strength and pelvic ROM. Knee extensor weakness is commonly observed in people with knee OA, and these individuals have an increased risk of functional decline (16). It seems that the ability to produce maximal voluntary eccentric force in the quadriceps is particularly reduced (17). Kierkegaard et al. (15) suggest future research could investigate the association between eccentric muscle strength and movement strategies during stair descent.

With this as a departure point, the research questions of this thesis are:

1) Do stair descent kinematics and leg strength differ between people with knee OA and healthy controls?
2) Does leg strength contribute to variance in joint angles during stair in people with knee OA?
3) Is there an association between self-reported difficulties and kinematics during stair descent in people with knee OA?

Upon embarking on this project, I expected to find:

- decreased knee flexion during weightbearing in OA cases compared to healthy controls
- that individuals with less knee flexion in the supporting leg might compensate by increasing adduction in the ipsilateral hip joint during stepping down
- that people with knee OA would generally be weaker than healthy controls, especially in eccentric knee extension

- an association between knee flexion angle during late single support and eccentric quadriceps strength
- that pain during strength testing could influence strength scores
- that there would be an association between self-reported difficulties descending stairs and knee-and hip angles, as well as temporal variables.

MATERIAL AND METHODS

The FUNKART project has a cross-sectional design, comparing knee OA cases to healthy controls of similar age and gender. The collected data includes measurements across all levels of the WHO's International Classification of Function (ICF) (18). In addition to self-reported subjective measures, a comprehensive test protocol was performed. All physical tests were carried out in the NTNU laboratory at Campus Tunga, with support from core facility NeXtMove. In this chapter, only measurements relevant for the current thesis are described.

Participants

Cases were recruited from physiotherapy clinics or outpatient hospital settings (patients referred by their General Physician to orthopedic surgeons). To be eligible for inclusion, cases had to meet the following criteria:

- 45 to 70 years old
- male or female
- clinically and radiologically diagnosed knee OA
    - main problem: Pain and limited physical function related to the knee(s)
    - symptomatic daily during a month
    - symptomatic for > three months

Healthy controls within the same age-range as the cases were recruited from hospital and academic staff and their network, and from the community in general. To be considered for inclusion, they had to be capable to walk on a flat floor and in stairs without pain.

Exclusion criteria (all participants):

- surgery to lower extremity < three years ago
- prior limb fractures
- generalized pain or competing pain from the spine, hip, or ankle
- body mass index > 35 kg/m^2
- arthroplastic knee surgery
- neurologic, rheumatic, or orthopedic diagnosis other than knee OA, which can negatively influence walking, balance, and pain

- insufficient understanding of Norwegian, in writing or in oral

Sample size calculations for the “parent” project (based on a previous pilot study), found that with a (two-tailed) α of 0.05, β 0.2, SD 0.7, and a moderate effect size of 0.64 for hip external rotation strength between groups, 20 participants would be needed in each group. To account for several outcome measures and possible withdrawal, this number was increased to 40 participants in each group.

Ethical considerations

The study was performed in accordance with the Helsinki declaration. Written and oral information about the project was provided to all participants, and written informed consent was obtained and securely stored. The project was approved by the regional ethics committee [2016/984/REK nord (2016/08.06)]. Data was anonymised and stored in a designated area on the NTNU server. Some of the data was registered by Infopad, which follows the *Norwegian Code of conduct for information security and data protection in the healthcare and care services* (19).

Stair test protocol

A freestanding staircase without railings was used for the stair test. The staircase consisted of three steps on each side of a plateau, and the step dimensions were as follows: Height 17 cm, tread 40 cm, width 75 cm. Participants wore short tights, and the test was performed barefoot. The subjects were instructed to walk the stairs, up and down, using their preferred pace. Further, they were directed to walk in a *forward* direction throughout the test. The test was performed four times, twice starting with their least affected (cases) or dominant (controls) leg, and twice starting with their most affected/ non-dominant leg (changing starting leg between each trial).

The test was recorded using Oqus capture system (Qualisys, Sweden) with eight cameras, a sampling rate of 120 Hz and 12 sec. capture periods. A standard calibration procedure for the space volume (according to the Qualisys manual) was performed.

For the static calibration procedure, 46 reflective markers were placed according to a setup based on a modified Helen Hayes model developed by Helena Grip (20). For the movement trials, the medial knee and ankle markers were removed in order to prevent frictional noise, leaving 42 markers (Fig. 1).

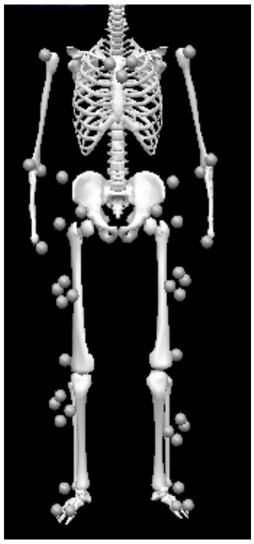

Fig. 1: Marker setup (42 markers). Sacrum marker not visible in figure.

Analyses of stair kinematics

Labelling and tracking of markers was performed in Qualisys Track Manager (QTM) version 2018.1 (Qualisys, Sweden). The second trial of each leg was chosen for analysis, unless the marker quality of the second trial made the file difficult to analyse.

Visual3D x64 Professional version 6.01.10 (C-motion, Maryland, USA) was used to build a model template, which was applied to the static calibration file and, in turn, the movement files. The signals were processed using a Butterworth bidirectional low-pass filter (cut-off frequency 6 Hz). Interpolation was used to estimate the trace in the case of gaps/ markers "disappearing" (maximum number of 10 frames).

A virtual distal foot marker was applied at the mean position between the medial and lateral forefoot markers. MatLab version 2018b (The MathWorks, Inc., Massachusetts, USA) was used to identify events: Toe-down was defined as the point in time when the derivative of the distal foot marker movement in the y dimension showed a local minimum, i.e., when the marker changed its direction of movement from onward to backward (21). Toe-off was defined as the time point when the distal foot marker reached its maximal velocity in the z (upward) dimension (22).

The events generated by the MatLab scrip were checked in Visual3D by visually inspecting both the velocity curves for the distal foot marker, as well as the model animations. For the majority of the data, the generated events corresponded well with the animations. In cases of discrepancy, events were moved "manually", frame by frame, to the point at which the forefoot markers started moving "backwards" and dorsiflexion of the ankle started to increase (toe-down) or the point at which the forefoot markers shifted their direction from “upward” to “onward” (toe-off).

For each leg, the analysis sequence started with ipsilateral toe-down and ended with ipsilateral toe-off, capturing the total stance phase. Contralateral toe-off and -down were also identified within this sequence, resulting in four events (Fig. 2).

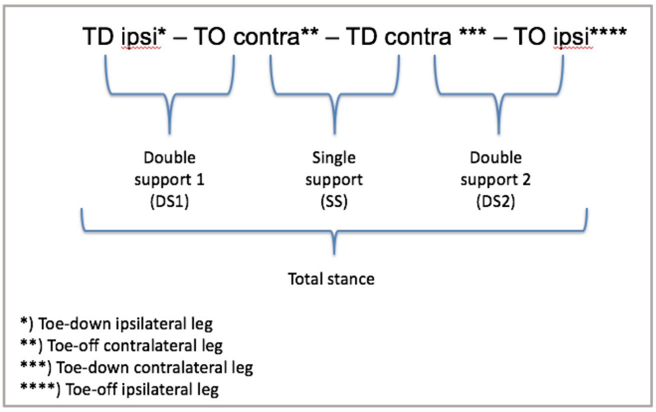

Fig. 2: Events and phases for stair descent analysis

Variables exported for further analyses included:

- Joint angles in the supporting leg at all four events for:
  - hip flexion/ extension, abduction/ adduction and internal/ external rotation
  - knee flexion/ extension
  - ankle plantar-/ dorsiflexion
- Duration (in seconds) of:
  - double support phase 1 (DS1): Toe-down ipsilateral foot → toe-off contralateral foot
  - single support phase (SS): Toe-off contralateral foot → toe-down contralateral foot
  - double support phase 2 (DS2): Toe-down contralateral foot → toe-off ipsilateral foot

Muscle strength protocol

Knee strength was measured using a Biodex dynamometer linked protocol (Biodex Medical Systems, New York, USA). The tests were performed in “passive mode”, as not all participants had a full active range of motion against gravity. After a “warm-up” of 15 light, active repetitions in each direction, a passive set of five repetitions at 60°/ sec. were performed, where the participants were instructed to do nothing at all and let the leg rest. This was followed by a set of five maximal concentric repetitions where participants were instructed to “help” the machine as much as possible. After a 30 seconds break, a set of five eccentric repetitions were performed, where they were instructed to resist the machine with maximal force. Biodex has been found to produce valid and reliable mechanical measurements (23), and similar peak torque measurements have been found between Biodex and Cybex for concentric and eccentric knee flexion/ extension (24). Yet, it should be mentioned that no validation studies performing these tests in "passive mode" were identified.

A handheld dynamometer (Commander Muscle Tester, JTech Medical Industries, Utah, USA) was used to measure hip abduction strength. The device was placed under a non-elastic fixation belt (art. no. 304018, Fysiopartner, Norway) that was looped around the lateral epicondyle of the femur and secured to a rigid fixture. This method has demonstrated reliable measurements for hip strength in healthy individuals (25, 26). The test was performed in supine with the hips oriented in a 0° anatomical position. Three maximal isometric repetitions were performed.

Analyses of strength data

For the knee tests, raw data from the passive, concentric and eccentric sets were imported into MatLab. A 9-point averaging filter was applied. The passive curves for each leg of each individual was estimated using a polyfit function on the data from the passive set. The concentric and eccentric curves were then corrected for passive forces by subtracting the estimated passive curve. Both the uncorrected and corrected curves were plotted graphically in order to evaluate their quality. Peak torque (maximal value of the five repetitions) was extracted for each muscle action. In addition, torque at 65° knee angle was extracted for eccentric knee strength (this angle represents the approximate mean knee angle at contralateral toe-down in healthy controls).

For hip abduction, peak torques registered by the handheld dynamometer were written down by hand and plotted digitally.

All strength measures were normalised to body weight for further analyses, as recommended by de Zwart et al. (27).

Self-reported measures

The Knee injury and Osteoarthritis Outcome Score (KOOS), item A1 (28), was used to assess self-reported difficulties descending stairs within the knee OA group. This questionnaire has been found to have good reliability, content- and construct validity for people with menisci- and cartilage injuries (29). Other relevant self-reported measures included pain during strength testing and the stair test, measured by the Numeric Rating Scale (NRS 0-10), and kinesiophobia score, measured by the Tampa Scale for Kinesiophobia (TSK) questionnaire (30).

Statistical analyses

All statistical analyses were carried out in SPSS version 25 (IBM, U.S.).

The full datasets were examined visually to identify possible missing values. Outliers in the strength and kinematic data were identified by boxplots and explored further to determine if they should be considered “valid” measurements. Consequently, one outlier in the strength data was excluded. The distribution of the different variables within each group and leg was assessed by QQ-plots, and Shapiro-Wilk was used to infer normality of the data (this test was chosen because of small sample sizes).

Further, boxplots were used to get an overall impression of the data, and to visualise joint angles of the supporting leg at the four different events. From the kinematic data, only joint angles at contralateral toe-down were used for further analyses. Descriptive data on joint angles at contralateral toe-down, temporal variables and muscle strength are presented as means ± 95% confidence intervals (CI). In addition, median ± interquartile range (IQR) are supplied for data not normally distributed.

As not all variables were normally distributed within groups/ legs, both parametric and non-parametric tests were performed to explore group differences. Means were compared using independent samples t-tests between healthy controls (mean of both legs) and the most and least affected leg, respectively, of the OA cases. Medians were compared using independent samples median tests and the Mann-Whitney U test.

It is common procedure to perform a Bonferroni correction when running multiple comparisons, in order to reduce the risk of type 1 errors. However, several authors have warned against using specific *p*-values to draw inference on hypothesises (31-33). For that reason, no alpha-level was set.

Linear mixed models were used to obtain adjusted group differences in joint angles and eccentric quadriceps strength, and to explore factors contributing to variance in knee and hip angles within the knee OA group. Leg index (most affected/ non-dominant vs. least affected/ dominant) was entered as a "repeated measure" with a diagonal covariance structure. Subject (ID) was entered as a random effect (random intercept). A selection of carefully selected fixed effects and interaction terms were added to build a "full" model (see "results" section). To control for the effect of *leg length* and *single stance duration* on joint angles, these variables were entered as covariates in the relevant analyses. Likewise, *age* and *pain during strength testing* were added as covariates in the strength models. Hurvich and Tsai's Criterion (AICc) was used to evaluate the model fit. Maximum Likelihood (ML) estimation was used when comparing different models on the same dependent variable, and Restricted Maximum Likelihood (REML) was used on the "final" model with the lowest AICc value. Normality of residuals was assessed by QQ-plots and normality tests (Kolmogorov-Smirnov or Shapiro-Wilk, depending on *n* of residuals). Homoscedasticity was assessed by residual plots. To explore the robustness of the models, they were run both with and without the most influential strength- and kinematic outliers.

Scatter plots were used to explore relationships between different variables and to investigate interaction effects.

Correlations between KOOS item A1 and kinematic, temporal, strength, pain and Tampa kinesiophobia scores were assessed by Spearman's Rho.

RESULTS

Of people who met the inclusion criteria for knee OA cases, 27 were recruited from an outpatient hospital setting, and two from physiotherapy clinics. One person later withdrew due to a flare-up, leaving 28 knee OA cases. The 31 healthy controls represented academic (n=10), administrative (n=6), health care personal (n=7), salespersons (n=3), industry employees (n=3) and canteen staff (n=2). The knee OA group were somewhat older than the healthy controls and, as expected, they reported more pain the previous week (Table 1). The reasons for declining were long traveling distances (n=3), not interested (n=4), afraid of strength testing (n=2), and too time-consuming (n=1). Five individuals with knee OA were declined participation due to age (n=3), BMI, and an unstable heart.

Table 1: Background descriptives of participants

	OA Group (n=28)	**Control Group (n=31)**	***p***
Gender (n F/M)	18/ 10	16/ 15	0.325
	Mean (SD)/ Median (IQR)		
Age (years)	61.7 (6.4)/ 62.0 (8.8)	55.3 (8.0)/ 53.0 (13.0)	0.003[a] 0.007[b]
BMI (kg/h^2)	28.0 (4.2)	26.9 (4.3)	0.316
Height (m)	1.72 (0.1)	1.74 (0.09)	0.509
Leg length (m)	0.907 (0.06)	0.912 (0.05)	0.762
Weight (kg)	82.9 (12.7)	80.4 (14.8)	0.511
Pain last week (NRS 0-10)	4.39 (2.3)/ 3.5 (4.8)	0.07 (0.25)/ 0.0 (0.0)	<0.001[a] <0.001[b]
KL grade most affected leg (0-4)	2.75 (0.59)	n/a	n/a
KL grade least affected leg (0-4)	1.50 (1.29)	n/a	n/a
Pain duration (months)	132.7 (101.6)	n/a	n/a
Pain during stair test (NRS 0-10)	1.4 (2.3) 0.0 (2.0)	0.0 (0.0)	0.011[a] 0.051[b]
TSK score	24.4 (7.7)	n/a	n/a
KOOS item A1	1.82 (1.22)	n/a	n/a

NRS= Numeric Rating Scale
KL= Kellgren-Lawrence
TSK= Tampa Score for Kinesiophobia
KOOS= the Knee injury and Osteoarthritis Outcome Score

[a]) Asymptotic *p*-value, Mann-Whitney U test
[b]) Asymptotic *p*-value, median test

One participant from the knee OA group was excluded from all kinematic analyses because he/ she did not descend the stairs in a step-over-step manner. Two healthy controls were excluded from the same analyses because of missing sacrum markers. Eccentric quadriceps and hamstrings peak torque could not be identified in one of the healthy controls. Eccentric quadriceps torque at 65° could not be identified in four healthy controls, in three *most affected* OA legs, and in one *least affected* OA leg. One healthy control displayed negative eccentric quadriceps torques (i.e. he/ she exerted force in the wrong direction) and was therefore excluded from the relevant analyses.

Differences between groups – Stair descent – Temporal variables

The knee OA group descended the stairs with longer stance phases, and they spent relatively more time in double support and less time in single support, compared to healthy controls (Table 2). The same pattern was seen for both legs.

Table 2: Group/ Leg means/ medians and differences in temporal variables

Temporal variables	**HC** (n=28)	**OA; MAL** (n= 27)	**OA; LAL** (n=25)	**HC (ref.) vs. OA; MAL**		**HC (ref.) vs. OA; LAL**	
	Mean (95% CI)	**Mean (95% CI) Median (IQR)**	**Mean (95% CI) Median (IQR)**	**Mean difference (95% CI)**	***p***	**Mean difference (95% CI)**	***p***
Total stance duration (sec.)	0.53 (0.49–0.57)	0.72 (0.65–0.79)	0.72 (0.64–0.80)	0.19 (0.11 to 0.26)	<0.001	0.18 (0.10 to 0.27)	<0.001
DS1 % of total stance	17.1 (15.1–19.2)	22.7 (21.2–24.3)	22.1 (20.6–23.7)	5.6 (3.1 to 8.1)	<0.001	5.0 (2.5 to 7.6)	<0.001
SS % of total stance	70.7 (67.4–74.0)	59.9 (57.5–62.4)	60.5 (58.0–63.0)	-10.8 (-14.8 to -6.8)	<0.001	-10.3 (-14.3 to -6.2)	<0.001
DS2 % of total stance	12.2 (10.4–13.9)	17.3 (15.7–18.9) 17.0 (3.5)	17.4 (15.0–19.8) 19.2 (7.8)	5.9[a] (?) 3.9[b] (?) 4.8[c] (2.7 to 7.2)	<0.001[d] <0.001[e]	5.1[a] (?) 6.1[b] (?) 5.7[c] (3.1 to 8.3)	<0.001[d] <0.001[e]

HC= Healthy Controls
OA; MAL= OA group, most affected leg
OA; LAL= OA group, least affected leg
DS1= 1st Double Support
SS= Single Support
DS2= 2nd Double Support

a) Geometric mean difference (data not normally distributed)
b) Sample median difference
c) Hodges-Lehman median difference
d) Asymptotic *p*-value, Mann-Whitney U test
e) Asymptotic *p*-value, median test
(?) CI could not be obtained

Differences between groups – Stair descent – Joint angles

The following boxplots serve as an overview of how joint angles changed throughout the stance phase (Fig. 3):

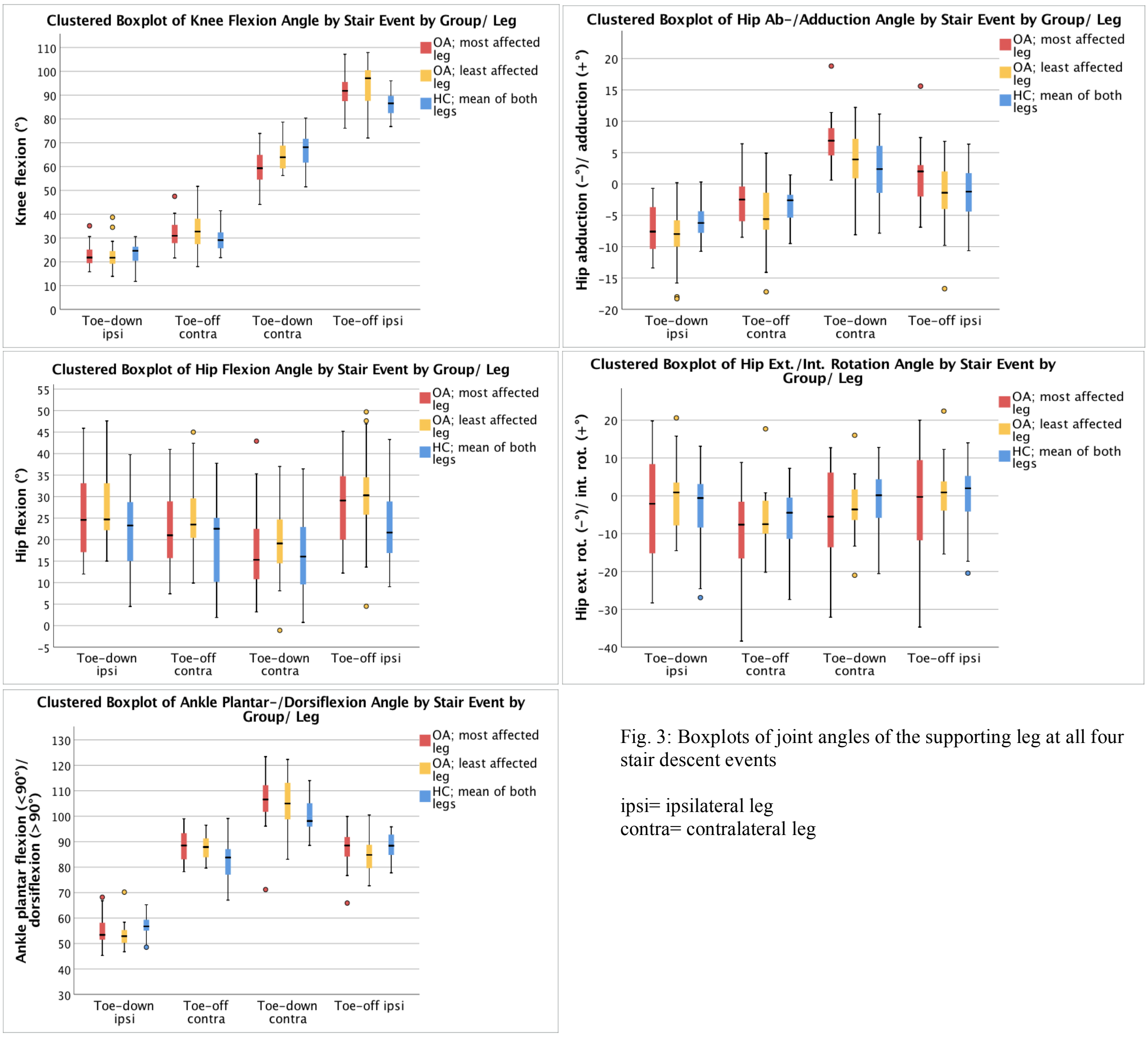

Fig. 3: Boxplots of joint angles of the supporting leg at all four stair descent events

ipsi= ipsilateral leg
contra= contralateral leg

Narrowing our attention to contralateral toe-down, the OA group had notably smaller knee flexion angles in their most affected leg compared to healthy controls. There were only minor differences in knee angles between the least affected leg and healthy controls (Table 3). The same pattern was seen for hip adduction, with the OA group displaying bigger angles at contralateral toe-down than healthy controls, especially in the most affected leg. The knee OA group also demonstrated greater ankle dorsiflexion than healthy controls.

Table 3: Group/ Leg means/ medians and differences in joint angles at contralateral toe-down

Angles at TD contra* (supporting leg)	HC (n=28)	OA; MAL (n=27)	OA; LAL (n=25)	HC (ref.) vs. OA; MAL		HC (ref.) vs. OA; LAL	
	Mean (95% CI)	Mean (95% CI) Median (IQR)	Mean (95% CI)	Mean difference (95% CI)	*p*	Mean difference (95% CI)	*p*
Knee flexion (°)	66.3 (63.1–69.5)	59.1 (56.3–62.0)	64.4 (61.8–67.0)	-7.2 (-11.4 to -3.0)	<0.001	-1.9 (-5.9 to 2.1)	0.344
Hip flexion (°)	16.6 (12.9–20.2)	17.6 (13.8–21.5)	19.9 (16.1–23.7)	1.1 (-4.1 to 6.3)	0.674	3.3 (-1.8 to 8.4)	0.203
Hip adduction (°)	2.2 (0.4–4.1)	6.8 (5.4–8.3) 6.9 (4.7)	4.1 (2.1–6.1)	4.5[b] (?) 4.5[c] (2.0 to 6.7)	<0.001[d] 0.005[e]	1.9 (-0.8 to 4.5)	0.165
Hip ext. (-°)/ int. (+°) rotation	-1.4 (-4.6–1.8)	-4.8 (-9.7–0.1)	-3.1 (-6.2–0.0)	-3.4 (-9.1 to 2.3)	0.241	-1.7 (-6.0 to 2.7)	0.447
Ankle PF (<90°)/ DF (>90°)	99.8 (97.2–102.4)	106.3 (102.3–110.3) 106.6 (11.2)	104.7 (100.6–108.9)	6.2[a] (?) 8.5[b] (?) 7.2[c] (3.2 to 11.8)	<0.001[d] 0.080[e]	4.9 (0.2 to 9.7)	0.043

*) Unadjusted
HC= Healthy Controls
OA; MAL= OA group, most affected leg
OA; LAL= OA group, least affected leg
PF= Plantar Flexion
DF= Dorsiflexion

[a]) Geometric mean difference (data not normally distributed)
[b]) Sample median difference
[c]) Hodges-Lehman median difference
[d]) Asymptotic *p*-value, Mann-Whitney U test
[e]) Asymptotic *p*-value, median test
(?) CI could not be obtained

After adjusting for leg length, single stance duration and random effects in the mixed model analyses, the OA group still had considerably smaller knee flexion angles in their most affected leg compared to healthy controls, but not in their least affected leg. The differences in hip adduction angles between healthy controls and the most affected leg of the OA group were still present. Ankle dorsiflexion was still greater in the OA group, but the difference was somewhat attenuated (Table 4).

Table 4: Results from linear mixed model analyses, angles, across groups

Dependent variable: Knee flexion (°) at TD contra			
Parameter	**Estimate**	**95% CI**	***p***
HC group (ref.)	65.73	.	.
OA most affected	-5.97	-9.57 to -2.38	0.001
OA least affected	-0.55	-4.12 to 3.02	0.758
Leg length (m)	-67.08	-95.05 to -39.10	< 0.001
Single stance duration (sec.)	-20.31	-40.12 to -0.49	0.045
Dependent variable: Hip adduction (°) at TD contra			
Parameter	**Estimate**	**95% CI**	***p***
HC group (ref)	2.45	.	.
OA most affected	+4.17	1.61 to 6.72	0.002
OA least affected	+1.40	-1.26 to 4.07	0.297
Leg length (m)	-12.84	-32.74 to 7.06	0.201
Single stance duration (sec)	+7.43	-7.30 to 22.16	0.319
Dependent variable: Ankle DF (°) at TD contra			
Parameter	**Estimate**	**95% CI**	***p***
HC group (ref)	102.78	.	.
OA most affected	+4.68	0.19 to 9.17	0.041
OA least affected	+3.27	-1.64 to 8.18	0.188
Single stance duration (sec.)	+29.26	2.68 to 55.84	0.031
Removed from final model based on AICc: Leg length (m): -7.49, 95% CI -41.69 to 26.71, *p*= 0.662 in full model			

Differences between groups – Strength

Strength scores for *all* knee muscle actions were considerably lower in the most affected leg of the knee OA group compared to healthy controls. Quadriceps strength was also reduced in the least affected leg of the OA group, but not to the same extent as in the most affected leg. Quadriceps strength was generally more reduced than hamstrings strength, and eccentric strength more reduced than concentric strength (Table 5).

Isometric hip abduction strength was also somewhat reduced in the knee OA group compared to healthy controls, with the greatest difference occurring in the least affected leg (Table 5).

Table 5: Group/ Leg means/ medians and differences in leg strength

Strength	HC (n= 31, 31, 29, 27, 30, 31)	OA; MAL (n= 28, 28, 28, 25, 28, 28)	OA; LAL (n= 28, 28, 28, 27, 28, 28)	HC (ref.) vs. OA; MAL		HC (ref.) vs. OA; LAL	
	Mean (95% CI)	**Mean (95% CI)**	**Mean (95% CI) Median (IQR)**	**Mean difference (95% CI)**	***p***	**Mean difference (95% CI)**	***P***
Norm. con. quad. peak torque (N/kg)	1.99 (1.82–2.17)	1.44 (1.23–1.65)	1.73 (1.53–1.93) 1.66 (0.60)	-0.55 (-0.82 to -0.28)	<0.001	-0.26[a] (?) -0.37[b] (?) -0.31[c] (-0.57 to -0.06)	<0.001[d] 0.026[e]
Norm. con. hams. peak torque (N/kg)	0.95 (0.85–1.05)	0.75 (0.64–0.85)	0.86 (0.74–0.98)	-0.20 (-0.34 to -0.06)	0.006	-0.09 (-0.24 to 0.07)	0.271
Norm. ecc. quad. peak torque (N/kg)	2.90 (2.64–3.17)	1.97 (1.67–2.28)	2.29 (1.93–2.65)	-0.93 (-1.33 to -0.54)	<0.001	-0.61 (-1.05 to -0.17)	0.007
Norm. ecc. quad. torque at 65° (N/kg)	2.62 (2.32–2.92)	1.70 (1.36–2.03)	2.06 (1.65–2.46)	-0.92 (-1.37 to -0.48)	<0.001	-0.56 (-1.06 to -0.07)	0.026
Norm. ecc. hams. peak torque (N/kg)	1.36 (1.25–1.48)	1.05 (0.90–1.20)	1.21 (1.03–1.39)	-0.31 (-0.50 to -0.13)	<0.001	-0.15 (-0.36 to 0.06)	0.149
Norm. isom. hip abduction peak torque (N/kg)	1.03 (0.92– 1.14)	0.90 (0.76 – 1.03)	0.85 (0.71 – 0.99)	-0.13 (-0.30 to 0.04)	0.127	-0.18 (-0.35 to 0.00)	0.045

HC= Healthy Controls
OA; MAL= OA group, most affected leg
OA; LAL= OA group, least affected leg

a) Geometric mean difference (data not normally distributed)
b) Sample median difference
c) Hodges-Lehman median difference
d) Asymptotic *p*-value, Mann-Whitney U test
e) Asymptotic *p*-value, median test
(?) CI could not be obtained

When adjusted for age and pain during strength testing (mixed model analyses), the group differences in eccentric quadriceps strength were attenuated, but still present to some degree (Table 6).

Table 6: Results from linear mixed model analyses, eccentric quadriceps strength, across groups

Dependent variable: Ecc. quad. torque at 65° (N/kg)			
Parameter	**Estimate**	**95% CI**	***p***
HC group (ref.)	2.40	.	.
OA most affected	-0.41	-1.00 to 0.18	0.171
OA least affected	-0.26	-0.80 to 0.29	0.354
Age (years)	-0.02	-0.05 to 0.01	0.189
Pain during strength test (NRS)	-0.08	-0.16 to -0.01	0.038
Outliers excluded from analysis: ID 112 (both legs). NRS= Numeric Rating Scale (0-10)			
Dependent variable: Ecc. quad. peak torque (N/kg)			
Parameter	**Estimate**	**95% CI**	***p***
HC group (ref.)	2.73	.	.
OA most affected	-0.55	-1.04 to -0.06	0.028
OA least affected	-0.40	-0.86 to -0.06	0.089
Age (years)	-0.01	-0.04 to 0.02	0.391
Pain during strength test (NRS)	-0.06	-0.11 to -0.00	0.041
Outliers excluded from analysis: ID 112 (both legs). NRS= Numeric Rating Scale (0-10)			

Variance in knee and hip angles within the knee OA group

Linear mixed models indicated that variance in knee flexion angle within the knee OA group was mainly accounted for by leg (most vs. least affected) and leg length (Table 7). There was no main effect of eccentric quadriceps strength, nor interaction effects between leg index and strength. Other variables that were included in the "full" model but excluded from the final model based on AICc values, included age, pain during stair test, kinesiophobia score (TSK) and interaction terms between leg index and these variables (Table 7).

Table 7: Results from linear mixed model analyses, knee flexion angle, within OA group

Dependent variable: Knee flexion (°) at TD contra			
Parameter	**Estimate**	**95% CI**	***p***
OA least affected (ref.)	64.21	.	.
OA most affected	-4.94	-8.01 to -1.87	0.003
Leg length (m)	-47.10	-81.34 to -12.87	0.009
Single stance duration (sec.)	-21.13	-45.26 to 3.00	0.084
Norm. ecc. quad. torque at 65° (N/kg)	0.06	-2.06 to 2.17	0.957
Removed from final model based on AICc: Age (*p*= 0.443), Pain during stair test (NRS) (*p*= 0.798), TSK score (*p*= 0.405), Leg * Leg length (*p*= 0.893), Leg * Single stance duration (*p*= 0.129), Leg * Age (*p*= 0.212), Leg * Norm. ecc. quad torque at 65° (*p*= 0.419), Leg * Pain during stair test (*p*= 0.836), Leg * TSK score (*p*= 0.307) in full model. NRS= Numeric Rating Scale (0-10) TSK= Tampa Scale for Kinesiophobia			

Table 8: Results from linear mixed model analyses, hip adduction angle, within OA group

Dependent variable: Hip adduction (°) at TD contra			
Parameter	**Estimate**	**95% CI**	***p***
OA least affected (ref.)	3.43	.	.
OA most affected	+2.71	0.42 to 5.00	0.022
Leg length (m)	+219.42	43.43 to 395.40	0.016
Knee flexion (°)	+3.56	0.91 to 6.21	0.010
Leg length * Knee flexion	-3.91	-6.81 to -1.00	0.010
Norm. isom. hip abd. peak torque (N/kg)	-0.01	-4.10 to 4.08	0.996
Removed from final model based on AICc: Norm. isom. hip abd. peak torque * Leg: *p*= 0.500 in full model			

Variance in hip adduction angle was accounted for by leg (most/ least affected), leg length, knee flexion angle and an interaction between knee flexion angle and leg length (Table 8). Further investigations using scatterplots labelled by leg length categories, revealed that in individuals with long legs, an increased hip adduction angle was associated with a smaller knee flexion angle, but not in individuals with short legs. There was no significant effect of isometric hip abduction strength, nor interaction effects of isometric hip abduction strength and leg index.

Self-reported difficulties and kinematics during stair descent

Correlational analyses showed no significant associations between self-reported difficulties descending stairs (KOOS item A1) and knee- or hip angles in the knee OA group. However, hip adduction angle in the most affected leg was slightly more correlated with self-reported difficulties than the other angles. A weak inverse correlation with eccentric quadriceps strength in the most affected leg was indicated by the correlation coefficient, although not necessarily of statistical importance. There was no obvious association with total stance duration. However, a weak correlation was found between self-reported difficulties and double support % of total stance. Moreover, self-reported difficulties were moderately correlated with pain during stair test and kinesiophobia scores (Table 9).

Table 9: Correlations between subjective difficulties descending stairs (KOOS item A1) and stair descent kinematics, strength, pain and kinesiophobia scores

KOOS item A1	Spearman's Rho	*p**
Total stance duration (sec.)	0.208	0.139
Double support % of total stance	0.335	0.010
Knee flexion (°) MAL / LAL	-0.112 / -0.132	0.578 / 0.530
Hip adduction (°) MAL / LAL	0.310 / -0.030	0.116 / 0.887
Norm. ecc. quad. torque at 65° (N/kg) MAL / LAL	-0.322 / -0.023	0.116 / 0.915
Pain during stair test (NRS)	0.510	< 0.001
TSK score	0.521	< 0.001
*) 2-tailed significance MAL= most affected leg LAL= least affected leg NRS= Numeric Rating Scale (0-10) TSK= Tampa Scale for Kinesiophobia		

DISCUSSION

The first aim of this thesis was to investigate differences in stair descent kinematics and leg strength between people with knee OA and healthy controls. The main results are discussed briefly in the following sections:

Differences in temporal variables

The knee OA group had a longer total stance than healthy controls. This was expected, considering the findings of decreased stair descent velocity in previous research (8-11). The increased total stance duration was mainly explained by longer double support phases, as the OA group spent relatively more time in double support compared to healthy controls. Similar observations were made by Hicks-Little *et al.* (10). They found that during stair descent, knee OA cases spent 17.7% (± 8.7) of the *total* gait cycle in double support, compared to 11.3% (± 3.3) in healthy controls.

In the current study, the knee OA cases were somewhat older than healthy controls. The question therefore arises whether this could explain the difference in total stance time, as age has been shown to influence stair descent speed in healthy adults (34). Scatterplots were used to investigate this relationship, which revealed that there was still a group difference in total stance time within an overlapping age range.

Differences in joint angles

Compared to healthy controls, the knee OA group displayed reduced knee flexion angles in their most affected leg at contralateral toe-down, also after adjusting for leg length and single stance duration. This difference was not explained by a restricted passive range of motion in the knee OA group, as the subjects obtained greater knee flexion angles at toe-off of the same limb. It could, on the other hand, reflect a compensatory strategy to decrease pain by reducing the internal extensor moments (8). Findings from previous research on knee angles during stair descent, have been inconsistent. Most studies have found somewhat smaller flexion angles in knee OA cases at *some point* during the descending task, although not necessarily significant. The heterogeneity between studies with regard to the chosen *events* for extracting knee angles, makes comparisons challenging: Some studies report *loading response* angles (11, 35), while others report *peak angle during support* (9, 12), angles at *contralateral toe-off*

(14) or yet other events (8, 13). In the current thesis, the events based on toe-down and -off of the two limbs were chosen because they mark the transitions between double and single support. Other issues complicating comparisons between studies, include variations in severity and compartmental location of knee OA, different test protocols (including stair dimensions) etc.

Further, the knee OA group demonstrated increased hip adduction angles at contralateral toe-down compared to healthy controls. This is not consistent with the findings of Doslikova (9) and Hicks-Little *et al.* (12). In their studies, the knee OA cases had slightly *smaller* peak adduction angles than controls during stance, although not deemed statistically significant. *Peak* angles are not reported in this thesis, and so accurate comparisons cannot be made. Nevertheless, an increased hip adduction angle in the stance leg is not unlikely in individuals displaying a reduced knee flexion angle (that is not explained by leg length alone). By adducting in the hip joint of the stance leg, less knee flexion is required to lower the swing leg to the next step, and this could represent a compensatory strategy (21, 34).

Differences in leg strength

The knee OA cases were generally weaker than healthy controls. This is in line with previous research (16, 17). However, the knee OA group reported more pain during strength testing, and when eccentric quadriceps scores were adjusted for this pain variable, the strength differences between the groups were attenuated. Pain has, indeed, been identified as one of several factors that may inhibit voluntary maximal force produced by the quadriceps (36). In a crossover, double-blinded trial, anesthetic or placebo fluid was injected in the symptomatic knees of 68 knee OA subjects (37). The researchers found a significant pain reduction after both injections, which was followed by a significant increase in isometric maximal voluntary contraction in the quadriceps. Whether eccentric strength scores would have been different in the absence of pain in the current study, is uncertain. One can imagine that, over time, pain inhibition of the muscles may result in actual strength deficits due to disuse. Also, it is well established that strength usually decreases with age (38), but the variance in strength accounted for by age was only minimal in the mixed model analyses.

The second aim of this thesis was to gain insight into the contribution of leg strength to variance in joint angles during stair descent in people with knee OA:

Variance in knee angles within the knee OA group

No associations were found between eccentric quadriceps strength and knee angles at contralateral toe-down in the knee OA group. Bennell *et al.* (39) found a weak association between isometric quadriceps strength and loading response knee flexion during stair descent, but to my knowledge no previous studies have investigated the relationship between *eccentric* quadriceps strength and knee angles.

Initially, a stronger relationship was expected between eccentric quadriceps torque at 65° and knee angles at contralateral toe-down, presuming that greater knee flexion during stair descent would demand more eccentric strength at the corresponding knee angles. However, this is not necessarily the case, as subjects may "drop" themselves down onto the next step with minimal eccentric work. Alternatively, one could imagine a "reverse causation", in which reduced knee flexion during stair descent could result in eccentric strength deficits at greater knee angles. When it comes to strength testing, some of the participants produced rather "messy" curves for the eccentric tasks. This could reflect difficulties understanding the task, or problems switching contraction mode (coordination). Furthermore, the knee strength tests were performed seated, with a greater hip flexion angle than obtained during stair descent. The length-tension relationship of the two-joint muscle rectus femoris is therefore different in the two situations. Whether these matters could affect the results on the relationship between stair descent angles and knee strength in this study, is less obvious.

Pain, or *pain avoidance*, is often hypothesized to explain altered kinematics and joint loading patterns during stair descent in people with knee OA (9, 11). In the current thesis, pain during stair descent did not account for variations in knee angles. This was somewhat expected, as people may differ in how they respond physically to pain. Whereas some individuals might relieve pain by decreasing knee flexion angles (and therefore report less pain), others might "allow" more pain to occur. Hinman *et al.* did, however, find a moderate inverse association between pain *at rest* and *total knee ROM* of the stance leg during stair decent in their study (11).

Variance in hip angles within the knee OA group

No clear relationship was found between hip abduction strength and hip adduction angle. However, an interaction effect between leg length and knee flexion angle was found, suggesting that in knee OA cases with longer legs, greater hip adduction was associated with decreased knee angles. The lack of association between these angles in individuals with shorter legs, could be explained by a "ceiling" effect of hip adduction, i.e. when the available adduction range of motion is used, they have to flex their knees more compared to those with longer legs, in order to achieve foot contact on the lower step. These findings strengthen the idea that increased hip adduction reflects a compensatory strategy, rather than a result of decreased hip strength. Yet, there is a possibility that the lack of association between hip strength and adduction angle could be partially attributed to different demands for the hip abductors in the two situations (isometric, supine vs. dynamic stabilisation during weightbearing).

The third aim of this thesis was to find out whether an association existed between self-reported difficulties and kinematics during stair descent in people with knee OA:

Self-reported difficulties and kinematics

There were no obvious correlations between subjective difficulties descending stairs and knee angles in this study. Hinman *et al.*, on the other hand, found a moderate inverse association between knee ROM and self-reported disability, as measured by The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) questionnaire (11). Further, in the current study, no clear associations were found between subjective difficulties and hip adduction angles or total stance time, only a weak inverse correlation with relative time spent in single support. This implies that altered kinematics do not necessarily represent a problem for people with knee OA. Perhaps, it could rather reflect a (compensatory) *solution* to a problem.

Methodological considerations

The stair test was performed in the participants' normal walking velocity. The effect of speed on angles during stair descent could have been controlled for using a metronome. However, this has been attempted in previous research, and proven to be difficult in practice (9, 11). The variance in angles due to velocity was therefore controlled for by incorporating single stance time in the mixed model analyses.

Furthermore, the staircase was not instrumented, so there was no available information on dynamics. This would have been desirable, as it would have made it easier to identify toe-down and -off, as well as provide information about moments acting on the knee at the different stages of the descent.

The staircase only had three steps. The first step down could be influenced by stepping pattern on top of the staircase (single vs. double step between ascending and descending). During the last step, foot markers disappeared for most of the participants. As a result, only one step was used for analyses (half a gait cycle). A staircase with more steps would have provided more information about within-subject variance in the variables of interest.

Only a limited selection of variables was explored in the current study. There is a possibility that other factors, such as knee stability, balance, body weight, psychological factors etc. could affect stair descent kinematics. It was, however, beyond the scope of this thesis to investigate all possible mechanisms.

In statistics, one is often advised to avoid multiple comparisons using the same means, as this increases the experiment-wise error rate (31). This could also be an issue in the current thesis. Yet, the *consistency* of the results is considered a strength in this context.

Linear mixed models have several benefits: They use both fixed and random effects as predictors, they allow non-independence of data, and they handle missing values. However, the complexity of these models can be demanding. Often, the assumptions of the models are violated (40). Attention has been paid to avoid such violations.

Finally, the cross-sectional design of this study does not allow for inference on causation.

Conclusion

- People with knee OA display altered kinematics during stair descent and reduced leg strength compared to healthy controls.
- Leg strength does not seem to explain variance in knee- or hip angles in this population.
- There is no clear association between subjective difficulties descending stairs and joint angles in people with knee OA, but a weak association with relative time spent in double support.

Clinical implications

Clinicians should be cautious not to view altered stair descent kinematics in people with knee OA as a "problem that needs to be solved", but rather as part of a symptomatic picture. It would, however, be interesting to see if improvements in pain levels and strength would be followed by changes in stair descent kinematics.

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