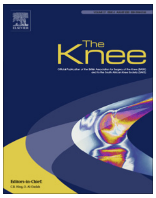
The Knee 33 (2021) 176–184

Contents lists available at ScienceDirect

The Knee

journal homepage:



Limited knee extension during gait after total knee arthroplasty is related to a low Oxford Knee Score

M.J. Booij[a,b,*], J. Harlaar[b,c,d], B.J. van Royen[b,e], P.A. Nolte[f], D. Haverkamp[g], J.C. van den Noort[b,h]

[a] *Amsterdam UMC, Vrije Universiteit Amsterdam, Department of Rehabilitation Medicine, Amsterdam, the Netherlands*
[b] *Amsterdam Movement Sciences, Amsterdam, the Netherlands*
[c] *Delft University of Technology, Department of Biomechanical Engineering, Delft, the Netherlands*
[d] *Erasmus Medical Center, Department of Orthopaedic Surgery, Rotterdam, the Netherlands*
[e] *Amsterdam UMC, University of Amsterdam, Department of Orthopaedic Surgery, Amsterdam, the Netherlands*
[f] *Spaarne Gasthuis, Department of Orthopaedic Surgery, Hoofddorp, the Netherlands*
[g] *Xpert Clinics, Department of Orthopaedic Surgery, Xpert Orthopedie Amsterdam/Specialized Center of Orthopedic Research and Education, Amsterdam, the Netherlands*
[h] *Amsterdam UMC, University of Amsterdam, Department of Radiology and Nuclear Medicine, Medical Imaging Quantification Center, Amsterdam, the Netherlands*

ARTICLE INFO

Article history:
Received 14 December 2020
Revised 24 May 2021
Accepted 25 August 2021

Keywords:
Total knee arthroplasty
Postoperative disability
Walking
Knee biomechanics

ABSTRACT

Background: After total knee replacement (TKR) some patients report low self-perceived function, which is clinically measured using patient reported outcome measures (PROMs). However, PROMs, e.g. the Oxford Knee Score (OKS), inherently lack objective parameters of knee function. Biomechanical gait analysis is an objective and reliable measurement to quantitatively assess joint function. Therefore, the aim of this study was to explore the relationship between biomechanical gait parameters and the OKS.
Methods: Gait analyses were recorded in 37 patients at least one year after primary TKR and in 24 healthy controls. Parameters from this analysis were calculated for hip, knee and ankle joint angles and joint moments in the sagittal and frontal plane including initial contact, early, late stance and swing. For the patients these parameters were expressed as its difference to control values at matched walking speed. Linear regression analyses were performed between the parameters from gait analysis and the OKS, with speed as covariate.
Results: The difference in knee extension angle at initial contact and late stance between patients and controls was significantly related to the OKS. Per one degree knee extension difference increase, the OKS reduced with 1.0 to 1.6 points. Overall, patients extended their knee less than controls. Neither ankle and hip gait parameters, nor joint moments showed a relation with OKS.
Conclusions: All patients with a submaximal score on the OKS showed limited knee extension during gait, even without a mechanical constraint in knee extension. This could be related to motor control limitations in this patient group.

---

* Corresponding author at: Amsterdam UMC, Vrije Universiteit Amsterdam, Department of Rehabilitation Medicine, Amsterdam, the Netherlands.
E-mail address: m.booij@amsterdamumc.nl (M.J. Booij).

https://doi.org/10.1016/j.knee.2021.08.025
0968-0160/© 2021 The Author(s). Published by Elsevier B.V.

1. Introduction

Despite the overall effectiveness of total knee replacement, about 16% of patients remains dissatisfied with their function one year after surgery [1]. Such functional limitations are commonly measured using patient reported outcome measures (PROMs). The cause of self-perceived dysfunction remains often elusive, since PROMs are subjective and influenced in a multifactorial manner [2,3]. Therefore, PROMs are unsuitable to support clinical decision making towards specific interventions, i.e. to identify a personalized intervention that a dissatisfied patient might profit from.

A more specific outcome of function after knee replacement surgery is the post-operative gait pattern. Gait analysis is a biomechanical evaluation of joint functions during gait. Such an objective and precise quantification may therefore potentially yield a meaningful specific outcome to evaluate function after knee replacement [4]. Rehabilitation programs already aim at improving patient mobility through walking-skill programs [5,6] and have shown to be effective to improve the gait pattern and distance walked. However, subjective and objective outcomes are both informative, each in their own manner. In these previous studies no specific objectives for gait parameters within these walking-skill programs are reported, neither clear relationships between gait patterns and self-perceived function have been identified in previous studies [7].

While gait analyses is an objective and useful method to evaluate joint function after knee replacement [4], the contribution of gait parameters to self-perceived function calls for attention. As a diagnostic tool, gait analysis might inform the surgeon how individual targets should be set within relevant interventions to improve post TKR patients' mobility and walking-skills.

Several studies have investigated the relationship between objective gait parameters and post-operative PROM scores [7–10]. However, only a very limited number of gait parameters were investigated. The findings on the presence of the relation between these specific gait parameters and PROM scores were inconsistent across individual studies [7–10]. Recently, over one hundred undefined gait parameters were found to be related to different PROMs [2].

Commonly applied PROMs to evaluate function after knee replacement surgery are the WOMAC, KOOS, KSS and OKS [11]. In this study it was chosen to investigate the Oxford Knee Score, which is specifically designed to evaluate knee pain and function outcome of knee replacement and considered valid and reliable [12,13].

Therefore, this study aims to explore which gait parameters of the lower extremities in knee replacement patients have a relation to the OKS.

2. Methods

Gait parameters were recorded of 37 patients one to five years after receiving their primary knee replacement because of severe knee osteoarthritis (Low Contact Stress Prosthesis (DePuy, USA) and ACS (Implantcast, Buxtehude, Germany) TiN mobile bearing prostheses types), included from multiple centers in the Netherlands. All patients were between 50 and 75 years old, BMI < 35 kg/m^2, could walk without aids and had no comorbidities that could affect the gait pattern, such as neurological disorders, or diagnosed osteoarthritis or a prosthesis in any other lower limb joint and no revision surgery was performed or planned the current knee implant, nor reported significant pain in other joints (VAS pain score over 3). Further, 22 gender- and age-matched asymptomatic, healthy participants without any joint replacements were included as a control group. Ethics approval was granted from the local Human Research Ethics Committees (NL51829.029.14), and written informed consent was provided according to the Committees' guidelines.

2.1. Data collection

Gait was collected on the GRAIL (Gait Real-time Analysis Interactive Lab, Motek ForceLink BV, Netherlands) at the rehabilitation department of the Amsterdam University Medical Center, location VUmc. Patients walked on an instrumented treadmill. During the walking trials, 3D motion was captured via InfraRed optical motion capture with wireless, light-reflecting markers (Vicon, Oxford, UK; measurement error < 0.22 mm [14]). 26 markers were placed on the patient for reconstruction of the position and orientation of the lower limbs, pelvis and trunk in space, according to the CAST model [15], recorded at a 100 Hz sample frequency. Additionally, ground reaction forces were measured using two 6D force plates, recorded at a 1000 Hz sample frequency.

First the preferred walking speed was determined at the treadmill. At this speed patients underwent a minimum of 5 minutes of habituation to treadmill walking, before gait data were recorded at the preferred walking speed for one minute.

After the gait recording, patients filled out the Oxford Knee Score (OKS) to assess knee pain and function. The OKS questionnaire is a 12-item questionnaire that evaluates functional ability on the level of body functions and activities and pain over the last week. Possible scores range from 0-48, with higher scores representing better function and less pain. The OKS is specifically designed for knee replacement patients and considered valid and reliable [12,13]. Also the Dutch version is shown to be valid [16].

2.2. Data processing

Marker and force plate data were filtered using a two-way second order low pass Butterworth filter with cut-off frequency of 6 Hz. Inverse kinematics and kinetics were performed using custom-made software BodyMech (www.body-mech.nl, Matlab 2018b, MathWorks, Natick, MA). For the leg with the knee replacement hip, knee and ankle sagittal and frontal kinematics (degrees) and kinetics (Ncm/kg) were calculated. All joint moments were expressed externally, expressed in the distal segment coordinate frame and normalized to body weight. Each gait cycle was time-normalized to one-hundred samples per cycle. In total 53 discrete parameters were calculated, including relevant peaks, range of motion over the full gait cycle and values at initial contact for the kinematic and kinetic waveforms (Fig. 1). Relevant peak parameters were

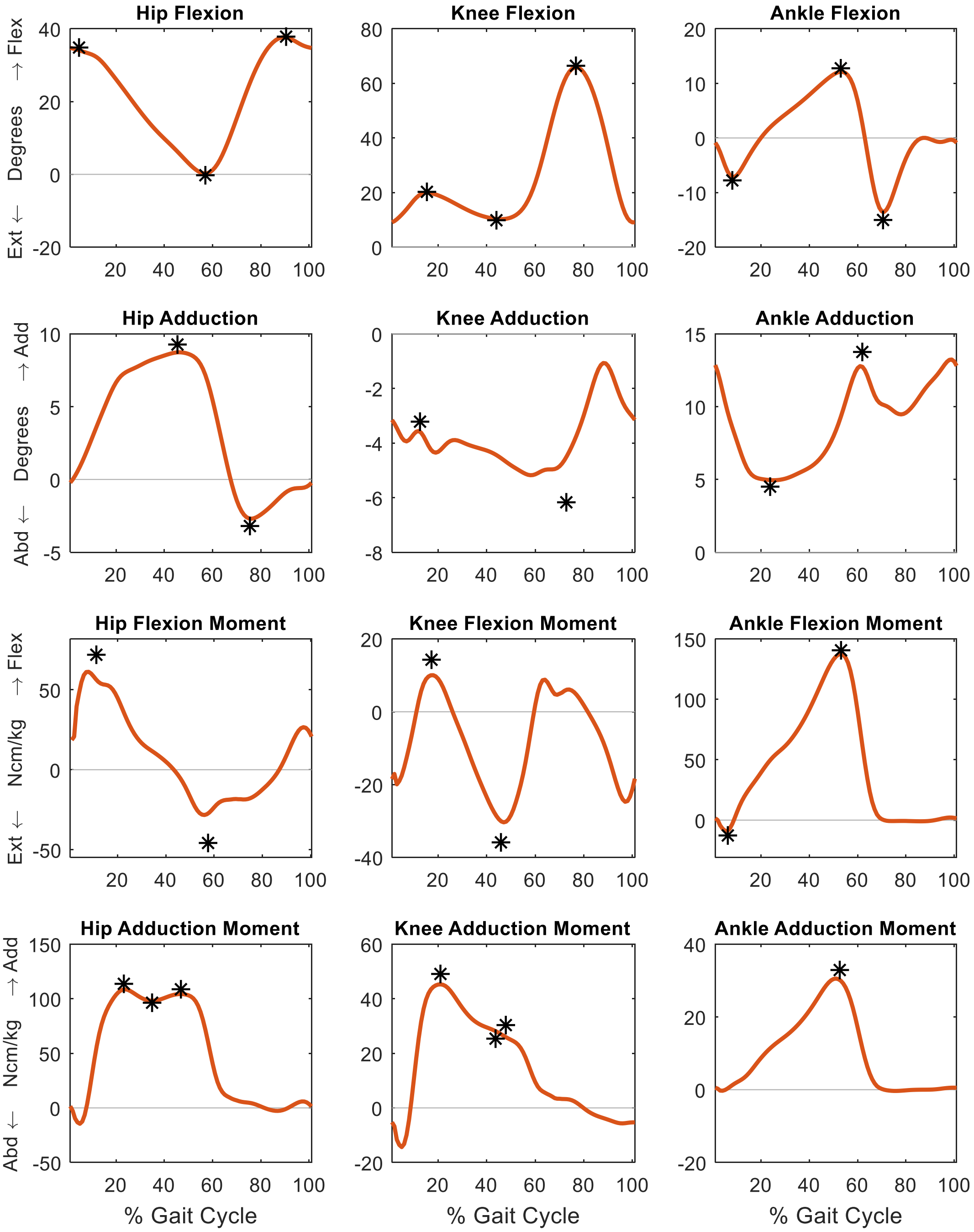


Fig. 1. Discrete parameters Visualization of the peak parameters (black asterisks) included in the study. These peak parameters are explored, in addition to the value at initial contact and range of motion over the full gait cycle (average gait cycle of the patient group shown in red).

calculated for within the following gait phases: early stance (1–20% of the gait cycle), midstance (20–40%), late stance (40%-toe-off (±66%)).

The parameters of the patient data were compared to the control group, by expressing the patient parameters as absolute deviation from control. These deviations were determined at matched walking speed, because differences in walking speed between knee replacement patients and controls can significantly impact the gait differences between these groups [17]. The gait biomechanics of the control group were matched to the walking speed of each patient separately using principal component analyses following the method of Meinders et al. 2021 [18]. Discrete parameters were calculated over each individual gait cycle and averaged over all gait cycles per patient. Finally, the deviation between the discrete parameters of the patients to the speed-matched controls were calculated.

2.3. Statistical analyses

Linear regression analyses were performed to determine whether there is an association between the patient deviations from controls of the 53 gait parameters and self-perceived function as measured by the OKS. Speed was added as a covariate to the regression analyses, to correct for differences in walking speed between patients. Addition of the covariate changed the regression coefficient with more than 10%, which confirms a relevant effect of speed [19]. In this study suboptimal functioning is investigated, therefore patients with a maximum score on the OKS should be excluded from the analyses, removing the ceiling effect [16]. This ceiling effect may otherwise skew the relation with the gait pattern.

Each variable was checked for normality using boxplot and histogram graphs. In case of the presence of extreme outliers (more than three times the interquartile range), this data point was removed from the linear regression analysis.

Significance was set at alpha is 0.05 and after a Bonferroni correction for multiple comparisons only tests with a p-value below 0.0009 were deemed significant.

All analyses were carried out in MATLAB R2018b (MathWorks, Natick, MA) and IBM SPSS Statistics version 26 (SPSS Inc. Chicago, IL, USA).

3. Results

After removal of the OKS ceiling score, 31 patients out of 37 patients remained for kinematic analyses. Due to technical issues 27 total knee replacement (TKR) patients were included for the kinetic analyses, due to failure of force data recordings from four patients. The TKR groups had a similar gender and age ($p > 0.10$), but a higher BMI and lower preferred walking speed ($p < 0.05$) compared to the control group (Table 1).

Only sagittal knee angle parameters showed significant relationships with the OKS (Fig. 2 & Table 2): a lower OKS score is related to more deviation from control gait. No significant relationships were found between gait kinetics and the OKS, nor between ankle and hip gait parameters and the OKS (Appendix A).

An extreme outlier was removed from the data of the range of motion of the knee flexion angle over the gait cycle (indicated as triangle in Fig. 2). Thus, only the knee extension angle at initial contact and at late stance remained to have a significant relation with the OKS score. At initial contact the knee extension showed the strongest effect size. At initial contact an increase of one degree knee extension deviation reduced to OKS score with 1.6 points, while at one degree at late stance reduced the OKS only 1.0 point (Table 2).

4. Discussion

In this study a strong correlation was found in knee replacement patients between greater knee extension deviation at initial contact and late stance and worse functioning as subjectively scored on the OKS. Knee extension during gait may therefore be a candidate to target in training programs, when patients report low self-perceived function.

Table 1 Patient and control characteristics.

	Patient Group		Control Group
	Kinematics	Kinetics	
Sample size (n)	31	27	22
Gender (%female)	42%	44%	41%
Age (years)	63.7 ± 5.3	64.2 ± 5.0	66.5 ± 5.2
BMI (kg/m^2)	28.1 ± 3.3	28.5 ± 3.3	25.8 ± 3.2
Age TKR (years)	2.0 ± 1.0	1.9 ± 0.7	n/a
Preferred walking speed (m/s)	1.0 ± 0.3	1.0 ± 0.3	1.2 ± 0.2
Matched walking speed (m/s)	n/a	n/a	1.0 ± 0.3

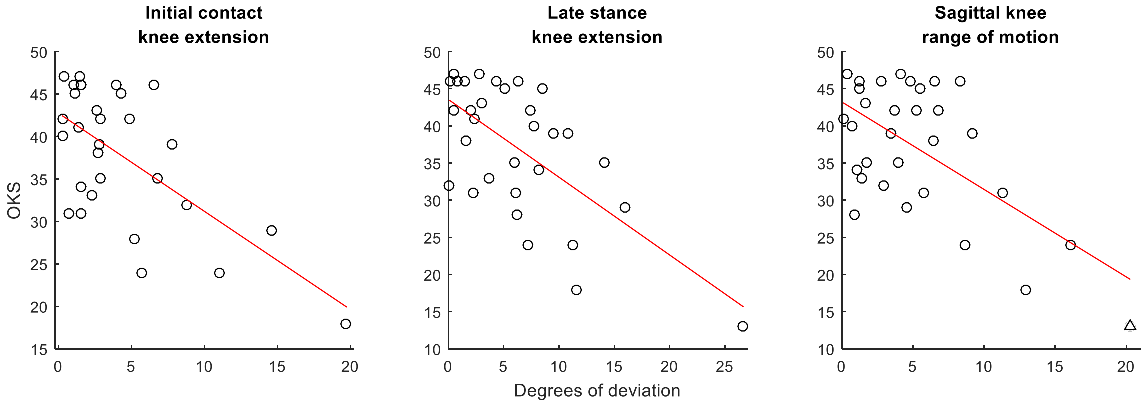


Fig. 2. Significant regressions with sagittal knee gait parameters, expressed as their absolute deviation from controls. Shown is the regression line without speed covariate, while speed was included in the analyses. The identified outlier is shown as triangle.

Table 2
Linear regressions between the Oxford Knee Score and gait biomechanics deviation.

	Beta Coefficient	Confidence Interval		p-value
		lower	upper	
Knee extension initial contact (°)	−1.627	−2.268	−0.989	**0.000***
Knee extension late stance (°)	−1.010	−1.525	−0.494	**0.000***
Sagittal knee range of motion (°)	−1.102	−1.727	−0.478	0.001◇

* Significant regression after correction for multiple testing.
◇ Significant regression without correction for multiple testing.

In agreement with our study, previous studies showed a relation between sagittal knee biomechanics during gait and self-perceived function [8–10] and no relations to ankle or hip biomechanics [7]. However, the studies investigating the knee biomechanics did not analyze knee extension specifically, but did find sagittal knee range of motion to be associated with self-perceived function. Most previous studies did not correct for multiple testing, nor removed ceiling scores or corrected for walking speed. The conservative statistical corrections in this study explains why we did not find the range in knee flexion related to self-perceived function and it underlines the importance of the remaining significant relations of knee extension during gait to self-perceived function. Unfortunately we cannot compare our outcomes to the study of Kirschberg et al. (2018), where almost 100 gait parameters were found to be related to function on the WOMAC, because these gait parameters were not specified. A full report of our testing can be found in Appendix A. Interestingly, even before correcting for multiple testing only two kinetic gait parameters have been found significantly related to OKS (Appendix A). A strong relationship between limited knee extension and the OKS was found, at initial contact and late stance. The regression outcome implies that with an increase of one degree knee angle extension limitation, the OKS decreases by 1.0–1.6 points. A small subset of patients (n = 6) scored below a score of 30 on the OKS, which is identified as the threshold for dissatisfaction with surgery outcome [20]. These patients with self-perceived dysfunction showed on average 14 and 13 degrees limitation in their knee extension angle at initial contact and late stance respectively. Based on the beta coefficients found for initial contact and late stance, these knee extension limitations have caused a decrease on the OKS score of 8 to 13 points, respectively. Therefore, the knee extension limitations found may have caused a clinically relevant reduction in self-perceived function, as the minimal clinically important difference for the OKS is five points [21].

All of the patient knee extension deviations were positive, i.e. patients landed on the leading leg with less knee extension than the control group (Appendix B). The relationships we found do not directly imply causal relationships. Still, limited knee extension may point towards an etiology that might be sensitive to treatment. Such a treatment effect might promote satisfaction in patients, to be subjected to further study. Limited knee extension after knee replacement may have a mechanical cause such as malposition of the implant or simply by its design [22], which would render patients not capable to further extend their knee. However, the physical exam showed that all patients with an unsatisfactory OKS score below 30 were capable to extend their knee at least eleven degrees further than they did on average during comfortable walking (Appendix B). Therefore, the limited knee extension was not caused by a mechanical constraint. The cause of the limited knee extension must therefore be sought in a disturbed motor control during comfortable walking in these patients.

Motor control can be disturbed for several reasons. The experience of prevalent symptoms after knee replacement, such as instability [23] and pain [24,25] are known to reduce knee extension. Also, gait deviations are often hypothesized to be a pre-operatively learned gait pattern [22,25] to comply with the pain of the arthritic knee. After years of symptomatic knee osteoarthritis, patients will have adjusted their gait pattern to these symptoms. This gait pattern may retain after knee replacement, although symptoms may have subsided. Such a gait pattern will be accompanied with increased co-contraction of the knee-spanning flexor and extensor muscles [23], which is inefficient and may increase loading of the knee and adjacent joints [26]. Therefore, it will be of importance for future research to identify the cause of limited knee extension that seems to be motor control related. A training program should aim for relearning, i.e. walking with more knee extension. Whether improvement of knee extension will lead to improvement of patients' self-perceived knee function can then be evaluated.

Previous studies have shown that TKR patients can be trained towards an improved gait pattern, although they used non-standardized targets, improvements were accompanied with improved PROM scores [27,28]. With a more focused training on knee extension targets, for instance with the application of biofeedback through virtual or augmented reality, such gait training may be even more effective [29].

Moreover, other gait parameters might be relevant for rehabilitation. A rather strict Bonferroni correction was applied in this study because of a large number of regression analyses. Future research might find the current borderline significant regressions significant, especially in larger sample sizes. A combination of gait parameters in the hip, knee and ankle might be stronger related to the self-perceived function. For such statistical analyses larger sample sizes are required.

A limitation of this study is the small number of patients with non-maximal OKS scores. Only six patients scored lower than 30. However, the relations found were highly significant. Future research could investigate whether inclusion of more dissatisfied patients leads to identification of more significant gait parameters of self-perceived function. However, this would require inclusion of large numbers of patients, since only 10–20% of patients is dissatisfied. Furthermore, only biomechanical gait deviations have been included as determinants for self-perceived function. Other factors may also need to be considered when aiming to improve self-perceived function, such as pre-operative function, patient characteristics, expectations and comorbidities [3,30,31].

The identified relations between the gait pattern and self-perceived function were only shown in two rather similar prostheses designs, using similar surgical techniques for placement of the prostheses. One should be careful with generalization of the results to the general population, because prosthesis design and surgical techniques may impact the rehabilitation of the gait function [32,33]. Furthermore, the rehabilitation of the patients was not controlled in this study. However, patients get a standardized amount of out-patient physiotherapy, for which national guidelines are drawn up (https://www.kngf2.nl/kennisplatform/guidelines).

Finally, we do not know whether our control group suffered asymptomatic knee osteoarthritis. X-rays could have shown whether osteoarthritis was present in the knee joints, but these were not taken from the controls. However, even minor symptoms were considered an exclusion criterion and clear deficits in range of motion would have been noticed during preparation of the measurements. Therefore, we feel our control group can be considered as free of any relevant comorbidities.

5. Conclusion

In this study we showed a strong significant relationship between limited knee extension during gait and poor OKS in knee replacement patients. Suboptimal self-perceived function was accompanied with limited knee extension during gait: for each degree knee extension limitation increase, the OKS decreases 1.0–1.6 points.

Ethical statement

The procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000. Ethical approval for this study was granted by the Medical Ethics Committee of the Amsterdam UMC, location VUmc.

All patients provided written consent for their participation in the study, prior to the obtaining of any research data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank all patients who participated in this study.

Author contributions

(1) Conception and design of the study – MB, JvdN, JH, BvR.
(2) Obtaining of funding - BvR.
(3) Collection and assembly of data – MB.
(4) Analysis and interpretation of the data – MB, JvdN.
(5) Provision of study patients – PN, DH.
(6) Drafting the article – MB, JvdN, JH, BvR.
(7) Critical revision of the article – MB, JvdN, JH, PN, DH.
(8) Final approval of the article – MB, JvdN, JH, BvR, PN, DH.
(9) Full integrity of the work as a whole from inception to finished article – MB.

Role of the funding source

This work was supported by the Dutch Arthritis Foundation, award reference LLP-23. There was no involvement of the study sponsors in this study.

Appendix A

See Tables 3 and 4.

Table 3
Kinematics. All calculated linear regressions between the Oxford Knee Score and kinematic gait parameters.

			Beta Coefficient	Confidence Interval		p-value
				lower	upper	
Hip	Sagittal	Peak early stance	0.01	−0.74	0.75	0.989
		Peak late stance	0.19	−0.37	0.75	0.496
		Peak swing	0.03	−0.91	0.97	0.949
		Range	−0.62	−1.18	−0.06	0.031[‡]
		Initial contact	0.02	−0.70	0.74	0.951
	Frontal	Peak stance	0.56	−0.55	1.66	0.311
		Peak swing	−0.67	−2.03	0.70	0.324
		Range	0.72	−0.34	1.77	0.176
		Initial contact	−0.69	−1.74	0.36	0.191
Knee	Sagittal	Peak early stance	−0.50	−1.01	0.01	0.052
		Peak late stance	−1.01	−1.53	−0.49	**0.000**[*]
		Peak swing	−0.69	−1.79	0.42	0.213
		Range	−1.10	−1.73	−0.48	0.001[‡]
		Initial contact	−1.63	−2.27	−0.99	**0.000**[*]
	Frontal	Peak early stance	0.05	−1.45	1.55	0.946
		Peak swing	−0.16	−1.12	0.80	0.728
		Range	0.48	−0.53	1.49	0.336
		Initial contact	−0.03	−1.54	1.49	0.970
Ankle	Sagittal	Peak early stance	−0.57	−1.73	0.59	0.325
		Peak late stance	−0.29	−1.22	0.64	0.530
		Peak swing	−0.55	−1.36	0.26	0.175
		Range	−0.03	−0.89	0.83	0.942
		Initial contact	−1.23	−2.12	−0.34	0.009[‡]
	Frontal	Peak early stance	−0.77	−1.48	−0.06	0.034[‡]
		Peak late stance	−0.64	−1.25	−0.03	0.041[‡]
		Range	0.74	−1.26	2.73	0.457
		Initial contact	−0.58	−1.20	0.05	0.070

[*] Significant regression after correction for multiple testing.
[‡] Significant regression without correction for multiple testing.

Table 4
Kinetics. All calculated linear regressions between the Oxford Knee Score and kinetic gait parameters.

			Beta Coefficient	Confidence Interval		p-value
				lower	upper	
Hip	Sagittal	Peak early stance	−0.11	−0.27	0.06	0.196
		Peak late stance	−0.13	−0.38	0.13	0.312
		Range	−0.09	−0.20	0.02	0.098
		Initial contact	−0.33	−0.71	0.05	0.083
	Frontal	Peak early stance	0.07	−0.19	0.32	0.593
		Peak midstance	0.09	−0.11	0.28	0.364
		Peak late stance	0.04	−0.17	0.24	0.721
		Range	−0.02	−0.30	0.27	0.915
		Initial contact	0.03	−0.84	0.89	0.953
Knee	Sagittal	Peak early stance	−0.05	−0.26	0.17	0.644
		Peak late stance	−0.09	−0.33	0.14	0.420
		Range	−0.09	−0.38	0.19	0.510
		Initial contact	−0.67	−1.34	0.00	0.049[‡]
	Frontal	Peak early stance	0.25	−0.10	0.60	0.151
		Peak midstance	0.17	−0.10	0.43	0.207
		Peak late stance	0.21	−0.06	0.47	0.117
		Range	0.06	−0.34	0.45	0.775
		Initial contact	−0.44	−2.27	1.39	0.627
Ankle	Sagittal	Peak early stance	−0.62	−1.66	0.41	0.225
		Peak late stance	0.11	−0.17	0.39	0.426
		Range	0.02	−0.24	0.29	0.862
		Initial contact	1.52	−5.57	8.55	0.660
	Frontal	Peak late stance	−0.36	−0.78	0.07	0.099
		Range	−0.56	−0.99	−0.12	0.014[‡]
		Initial contact	−7.77	−20.01	4.46	0.202

[*] Significant regression after correction for multiple testing.
[‡] Significant regression without correction for multiple testing.

Appendix B

See Table 5.

Table 5
Comparison of maximum passive knee extension during physical exam vs. knee extension during comfortable gait. Data shown for the patients with an unsatisfactory function OKS score (i.e. OKS < 30 [12]) above in the table and patients with the most satisfactory OKS score from the regression analyses (i.e. OKS > 45) in the lower half of the table.

		Comfortable gait (mean angle)				Physical exam
	OKS score	Knee extension deviation[◇] (patient – control knee flexion in degrees)		Knee extension angle (knee flexion in degrees)		Maximum knee extension (knee flexion in degrees)
		Initial contact	Late stance	Initial contact	Late stance	
OKS < 30	13	29.5	26.6	36.0	32.9	10
	18	19.7	11.6	26.2	17.9	0
	24	5.7	7.2	11.1	12.3	0
	24	11.1	11.3	17.1	17.1	0
	28	5.2	6.2	11.4	12.2	0
	29	14.6	15.9	20.5	21.6	0
	46	4.0	1.5	10.0	7.3	0
	46	6.6	0.2	11.5	4.9	0
OKS > 45	46	1.5	4.4	6.4	9.0	0
	46	1.5	0.8	3.3	5.3	0
	46	1.1	6.3	6.1	11.1	5
	47	1.4	0.5	4.1	5.9	0
	47	0.4	2.8	5.7	7.8	0

[◇] A positive deviation means more knee flexion than controls walking at the same speed.

References

[1] Clement ND, Macdonald D, Burnett R. Predicting patient satisfaction using the Oxford knee score : where do we draw the line ? Arch Orthop Trauma Surg 2013:689–94. doi: https://doi.org/10.1007/s00402-013-1728-3.

[2] Kirschberg J, Goralski S, Layher F, Sander K, Matziolis G. Normalized gait analysis parameters are closely related to patient-reported outcome measures after total knee arthroplasty. Arch Orthop Trauma Surg 2018;138(5):711–7. doi: https://doi.org/10.1007/s00402-018-2891-3.

[3] Kim TK, Chang CB, Kang YG, Kim SJ, Seong SC. Causes and Predictors of Patient's Dissatisfaction After Uncomplicated Total Knee Arthroplasty. J Arthroplasty 2009;24(2):263–71. doi: https://doi.org/10.1016/j.arth.2007.11.005.

[4] Mandeville DS, Osternig LR, Lantz BA, Mohler CG, Chou L-S. A multivariate statistical ranking of clinical and gait measures before and after total knee replacement. Gait Posture 2009;30(2):197–200. doi: https://doi.org/10.1016/j.gaitpost.2009.04.009.

[5] Bruun-Olsen V, Heiberg KE, Wahl AK, Mengshoel AM. The immediate and long-term effects of a walking-skill program compared to usual physiotherapy care in patients who have undergone total knee arthroplasty (TKA): a randomized controlled trial. Disabil Rehabil 2013;35 (23):2008–15. doi: https://doi.org/10.3109/09638288.2013.770084.

[6] Levinger P, Zeina D, Teshome AK, Skinner E, Begg R, Abbott JH. A real time biofeedback using Kinect and Wii to improve gait for post-total knee replacement rehabilitation: a case study report. Disabil Rehabil Assist Technol 2016;11(3):251–62. doi: https://doi.org/10.3109/17483107.2015.1080767.

[7] Liebensteiner MC, Herten A, Gstoettner M, Thaler M, Krismer M, Bach CM. Correlation between objective gait parameters and subjective score measurements before and after total knee arthroplasty. Knee 2008;15(6):461–6. doi: https://doi.org/10.1016/j.knee.2008.07.001.

[8] Turcot K, Sagawa Y, Fritschy D, Hoffmeyer P, Suvà D, Armand S. How gait and clinical outcomes contribute to patients' satisfaction three months following a total knee arthroplasty. J Arthroplasty 2013;28(8):1297–300. doi: https://doi.org/10.1016/j.arth.2013.01.031.

[9] Bonnefoy-Mazure A, Armand S, Sagawa Y, Suvà D, Miozzari H, Turcot K. Knee Kinematic and Clinical Outcomes Evolution before, Three Months and One Year Following Total knee Arthroplasty. J Arthroplasty 2016;32:793–800. doi: https://doi.org/10.1016/j.arth.2016.03.050.

[10] Naili JE, Wretenberg P, Lindgren V, Iversen MD, Hedström M, Broström EW. Improved knee biomechanics among patients reporting a good outcome in knee-related quality of life one year after total knee arthroplasty. BMC Musculoskelet Disord 2017;18:1–11. doi: https://doi.org/10.1186/s12891-017-1479-3.

[11] Ramkumar PN, Harris JD, Noble PC. Patient-reported outcome measures after total knee arthroplasty: a systematic review. Bone Jt Res 2015;4 (7):120–7. doi: https://doi.org/10.1302/2046-3758.47.2000380.

[12] Dawson J, Fitzpatrick R, Murray D, Carr A. Questionnaire on the perceptions of patients about total knee replacement. J Bone Joint Surg Br 1998;80:63–9. doi: https://doi.org/10.1302/0301-620x.78b5.0780856.

[13] Collins NJ, Misra D, Felson DT, Crossley KM, Roos EM. Measures of knee function: International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form, Knee Injury and Osteoarthritis Outcome Score (KOOS), Knee Injury and Osteoarthritis Outcome Score Physical Function Short Form (KOOS-PS), Knee Ou. Arthritis Care Res 2011;63(S11):S208–28. doi: https://doi.org/10.1002/acr.v63.11s10.1002/acr.20632.

[14] Windolf M, Götzen N, Morlock M. Systematic accuracy and precision analysis of video motion capturing systems-exemplified on the Vicon-460 system. J Biomech 2008;41(12):2776–80. doi: https://doi.org/10.1016/j.jbiomech.2008.06.024.

[15] Cappozzo A, Catani F, Della Croce U, Leardini A. Position and orientation in space of bones during movement: anatomical frame definition and determination. Clin Biomech 1995;10(4):171–8.

[16] Haverkamp D, Breugem SJM, Sierevelt IN, Blankevoort L, Dijk CNV. Translation and validation of the Dutch version of the Oxford 12-item knee questionnaire for knee arthroplasty. Acta Orthop 2005;76(3):347–52. doi: https://doi.org/10.1080/00016470510030814.

[17] Booij MJ, Meinders E, Sierevelt IN, Nolte PA, Harlaar J, van den Noort JC. Matching walking speed of controls affects identification of gait deviations in patients with a total knee replacement. Clin Biomech 2021;82:105278. doi: https://doi.org/10.1016/j.clinbiomech.2021.105278.

[18] Meinders E, Booij MJ, van den Noort JC, Harlaar J. How to compare knee kinetics at different walking speeds? Gait Posture 2021;88:225–30. doi: https://doi.org/10.1016/j.gaitpost.2021.06.004.

[19] Twisk JWR, editor. Inleiding in de toegepaste biostatistiek. Houten: Bohn Stafleu van Loghum; 2016.

[20] Judge A, Arden NK, Cooper C, Kassim Javaid M, Carr AJ, Field RE, et al. Predictors of outcomes of total knee replacement surgery. Rheumatology (Oxford) 2012;51(10):1804–13. doi: https://doi.org/10.1093/rheumatology/kes075.

[21] Clement ND, MacDonald D, Simpson AHRW. The minimal clinically important difference in the Oxford knee score and Short Form 12 score after total knee arthroplasty. Knee Surg Sport Traumatol Arthrosc 2014;22(8):1933–9. doi: https://doi.org/10.1007/s00167-013-2776-5.

[22] Saari T, Tranberg R, Zügner R, Uvehammer J, Kärrholm J. Changed gait pattern in patients with total knee arthroplasty but minimal influence of tibial insert design. Acta Orthop 2005;76(2):253–60. doi: https://doi.org/10.1080/00016470510030661.

[23] Ardestani MM, Malloy P, Nam D, Rosenberg AG, Wimmer MA. TKA patients with unsatisfying knee function show changes in neuromotor synergy pattern but not joint biomechanics. J Electromyogr Kinesiol 2017;37:90–100. doi: https://doi.org/10.1016/j.jelekin.2017.09.006.

[24] Kaufman KR, Hughes C, Morrey BF, Morrey M, An K-N. Gait characteristics of patients with knee osteoarthritis. J Biomech 2001;34(7):907–15. doi: https://doi.org/10.1016/S0021-9290(01)00036-7.

[25] Mizner RL, Snyder-Mackler L. Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. J Orthop Res 2005;23(5):1083–90. doi: https://doi.org/10.1016/j.orthres.2005.01.021.

[26] Richards RE, Andersen MS, Harlaar J, van den Noort JC. Relationship between knee joint contact forces and external knee joint moments in patients with medial knee osteoarthritis - effects of gait modifications. Osteoarthr Cartil 2018;26(9):1203–14. doi: https://doi.org/10.1016/j.joca.2018.04.011.

[27] McClelland J, Zeni J, Haley RM, Snyder-Mackler L. Functional and Biomechanical Outcomes After Using Biofeedback for Retraining Symmetrical Movement Patterns After Total Knee Arthroplasty: A Case Report. J Orthop Sport Phys Ther 2012;42(2):135–44. doi: https://doi.org/10.2519/jospt.2012.3773.

[28] Pfeufer D, Gililland J, Böcker W, Kammerlander C, Anderson M, Krähenbühl N, et al. Training with biofeedback devices improves clinical outcome compared to usual care in patients with unilateral TKA: a systematic review. Knee Surgery, Sport Traumatol Arthrosc 2019;27(5):1611–20. doi: https://doi.org/10.1007/s00167-018-5217-7.

[29] Richards RE, van den Noort JC, van der Esch M, Booij MJ, Harlaar J. Effect of real-time biofeedback on peak knee adduction moment in patients with medial knee osteoarthritis: Is direct feedback effective? Clin Biomech 2018;57:150–8. doi: https://doi.org/10.1016/j.clinbiomech.2017.07.004.

[30] Munin MC, Kwoh CK, Glynn N, Crossett L, Rubash HE. Predicting discharge outcome after elective hip and knee arthroplasty. Am J Phys Med Rehabil 1995;74(4):294–301. doi: https://doi.org/10.1097/00002060-199507000-00006.

[31] Jones CA, Voaklander DC, Suarez-Alma ME. Determinants of function after total knee arthroplasty. Phys Ther 2003;83:696–706. doi: https://doi.org/10.1093/ptj/83.8.696.

[32] Dennis D, Komistek R, Stiehl J, Walker S, Dennis K. Range of Motion After Total Knee Arthroplasty The Effect of Implant Design and Weight-Bearing Conditions. J Arthroplasty 1998;13:748–52. doi: https://doi.org/10.1016/S0883-5403(98)90025-0.

[33] Sheth NP, Husain A, Nelson CL. Surgical Techniques for Total Knee Arthroplasty: Measured Resection, Gap Balancing, and Hybrid. J Am Acad Orthop Surg 2017;25(7):499–508. doi: https://doi.org/10.5435/JAAOS-D-14-00320.