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Gait quality assessed by trunk accelerometry after total knee arthroplasty and its association with patient related outcome measures

Bas L. Fransen[a,b,*], Nina M.C. Mathijssen[c], Karin Slot[a], Nicole H.H. de Esch[c], Hennie Verburg[c], Olivier P.P. Temmerman[a], Marco J.M. Hoozemans[a,b], Jaap H. van Dieën[b]

[a] CORAL – Centre for Orthopaedic Research Alkmaar, Department of Orthopaedic Surgery, Noordwest Ziekenhuisgroep Alkmaar, Wilhelminalaan 12, 1815 JD Alkmaar, the Netherlands

[b] Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam Movement Sciences, Van der Boechorststraat 9, 1081 BT Amsterdam, the Netherlands

[c] Department of Orthopaedic Surgery, Reinier de Graaf Hospital, Reinier de Graafweg 5, 2625 AD Delft, the Netherlands

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ABSTRACT

Background: With an increasingly younger population and more active patients, assessment of functional outcome is more important than ever in patients undergoing total knee arthroplasty. Accelerometers have been used successfully to objectively evaluate gait quality in other fields. The aim of this study was to assess gait quality with accelerometers before and after surgery, and to assess added value of resulting parameters to patient reported outcome measures scores.

Methods: Sixty-five patients (mean age 65 years (range 41–75)) who underwent primary total knee arthroplasty were evaluated using a tri-axial trunk accelerometer preoperatively and 1 year after surgery. Gait quality parameters derived from the accelerometry data were evaluated in three dimensions at both time points. Factor analysis was performed on all outcome variables and changes from before to 1 year after surgery in the most representative variable for each factor were studied.

Findings: Factor analysis identified three separate gait quality factors, with questionnaire and gait quality parameters loading on different factors. Both gait quality factor scores and questionnaire factor scores improved significantly 1 year after surgery. As expected based on the factor analysis, only weak to moderate associations were found between patient reported outcome measures and gait quality before surgery, after surgery and in change scores.

Interpretation: The independence of patient reported outcome measures and gait quality parameters measured with trunk accelerometry indicates that gait quality parameters provide additional information on functional outcome after total knee arthroplasty. Providing caretakers with objectively measurable targets using accelerometry could help improve outcome of these patients.

1. Introduction

Osteoarthritis (OA) of the knee is a degenerative joint disease, disabling approximately 6% of the adults of 30 years and older (Felson et al., 2000). Total knee arthroplasty (TKA) is successfully used to treat moderate to severe OA. During the last decades, the prevalence of OA and the number of TKAs has increased strongly and is expected to increase further, because of demographic trends in obesity and life expectancy and because TKAs are increasingly performed in younger patients (Inacio et al., 2017; Wallace et al., 2017). To measure clinical outcome and monitor the results of TKA, mostly patient reported outcome measures (PROMs) are used. These questionnaires allow patients to report their quality of life, level of functioning and other outcome variables, and are used because they have a high internal consistency, are relatively easy to complete, and are cost-effective (Stevens-Lapsley et al., 2011). There are indications that PROMs may not fully capture the details of limitations in patient functional performance after TKA (Abbasibafghi, 2012). This might be partially due to the fact that PROMs outcome is influenced by, amongst others: pain, patient expectations, function of the non-operated limb, and functional status before the surgery (Jacobs and Christensen, 2009; Stevens-Lapsley et al., 2011). Because of the increased number of relatively

* Corresponding author at: CORAL – Center for Orthopaedic Research Alkmaar, Noordwest Ziekenhuis Alkmaar, Department of Orthopaedics, Wilhelminalaan 12, 1815 JD Alkmaar, the Netherlands.

E-mail address: b.l.fransen@nwz.nl (B.L. Fransen).

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young patients undergoing TKA surgery and patients remaining active to an older age, recovery of functional abilities has become increasingly important in a patient who has undergone a TKA. It could therefore be argued that more detailed analysis of functional outcome, especially gait, could be of added value and could give a better understanding of changes in functional performance after TKA (Bolink et al., 2015; Jacobs and Christensen, 2009).

More detailed gait analysis of TKA patients using accelerometers, aimed at spatiotemporal parameters in short bouts of gait, has already provided indications that objective functional measurements can be an addition to clinical outcome measured with subjective PROMs (Kluge et al., 2018). Using accelerometers, quality of gait measurements can be assessed in a clinical or domestic setting, in larger cohorts of patients, and in a relatively inexpensive way (van der Straaten et al., 2017). These earlier studies were done in smaller groups, and did not determine the added value of gait quality to the assessment of PROMs. Also, no trunk accelerometry has been used, which has shown to be a valid and reliable method to objectively assess gait quality (van der Straaten et al., 2017). With trunk accelerometry, an accelerometer is placed at the lower lumbar spine, which allows the device to collect data on gait stability, symmetry, and smoothness, as well as spatiotemporal gait features (Rispens et al., 2014). Therefore, analysis of gait quality using trunk accelerometry in TKA patients could provide a more detailed analysis of symmetry, stability and smoothness of gait in these patients, in addition to clinical outcome assessed using PROMs.

The goal of the present study was to use trunk accelerometers for instrumented analysis of gait quality parameters (i.e. stability, symmetry, and smoothness) of patients before and 1 year after unilateral primary TKA. The associations between these parameters and several commonly used PROMs were studied, to provide insight into whether gait quality parameters contain independent information on functional outcome after TKA that could be an addition to PROMs.

Table 1
Study inclusion and exclusion criteria.

Inclusion criteria
• Patient is 18 to 75 years of age. • Patient qualifies for a primary total knee arthroplasty based on physical exam and medical history, including diagnosis of severe knee pain and disability due to at least one of the following: o Rheumatoid arthritis, osteoarthritis, traumatic arthritis, polyarthritis o Collagen disorders and/or avascular necrosis of the femoral condyle o Post-traumatic loss of joint configuration, particularly when there is patellofemoral erosion, dysfunction or prior patellectomy o Moderate valgus, varus, or flexion deformities o The salvage of previously failed surgical attempts that did not include partial or total knee arthroplasty of the ipsilateral knee • Patient is willing and able to complete scheduled study procedures and follow-up evaluations
Exclusion criteria
• Patient is currently participating in any other surgical intervention studies or pain management studies • Previous history of infection in the affected joint and/or other local/systemic infection that may affect the prosthetic joint • Insufficient bone stock on femoral or tibial surfaces • Skeletal immaturity • Neuropathic arthropathy • Osteoporosis or any loss of musculature or neuromuscular disease that compromises the affected limb • Stable, painless arthrodesis in a satisfactory functional position • Severe instability secondary to the absence of collateral ligament integrity • Rheumatoid arthritis accompanied by an ulcer of the skin or a history of recurrent breakdown of the skin • Patient has a known or suspected sensitivity or allergy to one or more of the implant materials • Patient is pregnant • Patient is considered a member of a protected population (e.g., prisoner, mentally incompetent, etc.) • Patient has previously received partial or total knee arthroplasty for the ipsilateral knee.

2. Methods

2.1. Study design and study population

A prospective multicenter, observational study was performed in two large non-university teaching hospitals in The Netherlands between 1 July 2014 and 1 July 2017. This study was performed in accordance with the Declaration of Helsinki (*JAMA*, 2013). Institutional review board approval was received from the Medical Ethical Committee Zuidwest Holland (number 14-071), and the study was registered in the Dutch Trial Register (number NTR6566). Eligible patients who were planned to undergo a primary TKA were approached and evaluated to check if they met in- and exclusion criteria (Table 1). To have the study population represent an actual orthopaedic population, it was decided to include patients regardless of whether they had undergone previous arthroplasty in other joints or whether they mobilized using walking aids. After inclusion, all patients signed an informed consent form. All participants underwent preoperative clinical evaluations prior to their TKA and were evaluated again 1 year after surgery. A sample size of at least 50 patients was deemed adequate to have sufficient statistical power to detect relevant changes in gait parameters as calculated by Toebes et al. (Toebes et al., 2016) and to be sufficient for the correlational analysis performed. All patients received a Persona cemented total knee prosthesis (Zimmer-Biomet, Warsaw, USA).

2.2. Gait quality

Gait analysis was performed using the Dynaport Hybrid system (McRoberts, The Hague, The Netherlands), which uses a triaxial accelerometer for assessment in anteroposterior (AP), mediolateral (ML), and vertical (VT) direction. The accelerometer used a range from −6 g to 6 g, with the sample rate set to 100 samples per second. The accelerometer was placed on the back of the patient at the level of the sacrum using an elastic velcro belt. To ensure that patients' gait quality was optimal, measurements were done in the outpatient clinic on a level surface without distractions. Patients were then instructed to walk 2 × 50 meters in this setting at a self-selected pace both before and 1 year after the operation, with a researcher monitoring them. Stride time variability (STV), low frequency percentage (LFP), gait smoothness (GS), dominant frequency amplitude (DFA), gait symmetry (harmonic ratio, HR) and stride regularity (SR) were calculated using custom MATLAB scripts (MathWorks, Natick, USA). These gait characteristics have been described previously and were successfully used before to evaluate gait quality (Rispens et al., 2014; Rispens et al., 2016). Higher values for GS, DFA, HR and SR indicate better gait quality, whereas for STV and LFP lower values indicate better gait quality. Patients were also instructed to walk 10 m twice whilst being timed. From this, the average walking speed in meters/s was calculated.

2.3. PROMs

Patients were asked to complete several questionnaires before surgery and one year after surgery: the Oxford Knee Score (OKS) (Haverkamp et al., 2005), which has scores ranging from 0 (best) to 48 (worst); the Knee Disability and Osteoarthritis Outcome Score (KOOS) (de Groot et al., 2008), which has five subscores each ranging from 0 (worst) to 100 (best) and the EQ-5D-3L, using the Dutch tariff (Lamers et al., 2006) with a higher score indicating higher quality of life, and included a visual analogue scale (VAS) for quality of life (QoL), ranging from 0 (worst) to 100 (best).

2.4. Statistical analysis

All statistical analyses were done using IBM SPSS Statistic version

23 (IBM Corporation, Armonk, NY, USA). A principal axis factor analysis was performed on the preoperative measurements, to cluster the parameters into a limited number of factors. To prevent multicollinearity in the analysis, inter-correlations were checked for $r > 0.8$. DFA-VT and the pain and ADL subscores of the KOOS were not entered into the factor analysis because of (multiple) inter-correlations higher than 0.8. GS-AP and DFA-AP were excluded after the individual Kaiser–Meyer–Olkin (KMO) test resulted in a value < 0.5, indicating unsuitability for factor analysis. The remaining 19 outcome variables were used as input in the factor analysis. The KMO test was also used to verify the sampling adequacy considering a KMO > 0.5 and Bartlett's test of sphericity was checked for significance. The number of extracted factors was defined based on Kaiser's criterion with eigenvalues larger than one (Kaiser, 1960). VariMax rotation was used to optimize the loading of variables onto factors.

The most representative variable for each factor was used for an analysis of changes in function between measurements before and after surgery. Normality of the difference between the values of the selected outcome parameters was assessed by visual inspection of the histograms and q-q plots and using the Kolmogorov–Smirnov test. Since most differences showed a skewed distribution, differences were analyzed using non-parametric Wilcoxon signed-rank tests. To further quantify the degree of independence between PROMs and gait quality parameters, correlations between PROMs and gait quality parameters were calculated using Spearman's Rho for baseline, 1 year postoperative and delta scores (the difference between postoperative and preoperative scores). A Spearman's Rho value of 0.5 or higher was considered a strong association, 0.3–0.5 was considered moderate and 0.1–0.3 was considered a weak association (Cohen, 1988).

3. Results

3.1. Study population

Sixty-five patients with an average age of 65 years (range 41–75) completed the entire protocol. 54% of the patients were female, and the average BMI was 30 (range 19 to 56). Patient characteristics can be found in Table 2.

3.2. Factor analysis

The initial factor analysis on PROMS and gait quality parameters resulted in the identification of five factors with eigenvalues above 1.0 (> 1.157), which in combination explained 62% of the variance. However, the fifth factor consisted of GS-VT only (with a factor loading of 0.550). The final factor analysis was, therefore, forced into identifying four factors, the loadings of which after rotation are presented in Table 3. The sampling was considered adequate with a KMO of 0.744, and all individual KMO values were higher than 0.565. For this factor analysis, the lowest eigenvalue observed was 1.611 and the four factors combined explained 58% of the variance (Table 3). The four factors were defined as 'AP/VT gait quality', accounting for 24% of the variance, 'PROMs' (14%), 'Symmetry' (10%) and 'ML gait quality' (9%).

Table 2
Characteristics of all included patients.

	N = 65
Age (years) at time of surgery	65 (41–75)
Gender	
Female	35
Male	30
BMI (kg/m^2)	30 (19–56)
Side for TKA	
Left	28
Right	37
ASA classification	
1	14
2	48
3	3
Type of anesthesia	
Spinal/epidural	56
General	9
Duration of surgery (minutes)	66 (52–120)

Data in mean (min–max), or number.

The parameters having the highest factor loadings for the four factors were selected: for 'AP/VT gait quality', this was stride regularity-VT with a loading of −0.883, for 'PROMs', this was the OKS with a loading of −0.922, for 'Symmetry', harmonic ratio-AP with a value of 0.787, and for 'ML gait quality', it was stride regularity-ML with a factor loading of 0.784.

3.3. Factor scores and correlations

The baseline and postoperative scores of the most representative variables for each of the four factors are presented in Table 4. All of these variables improved significantly. Correlations between the selected gait parameters and PROMs scores were calculated for the measurements before surgery, 1 year after surgery, and for delta values (i.e., differences between before and after surgery). Five of the nine associations were statistically significant (Table 5). Out of these five, the associations between stride regularity-VT and OKS at baseline and for delta values, and the association between stride regularity-ML and OKS for delta values were moderate (Spearman's rho values between 0.3 and 0.5). The associations between harmonic ratio-AP and the OKS at baseline and 1-year follow-up were weak (Spearman's rho values between 0.1 and 0.3). Correlations between all gait parameters and PROMs scores can be found in Supplementary Tables 1A–C. The scores of all gait quality parameters and PROMs are presented in Supplementary Tables 2 and 3, respectively.

4. Discussion

We performed a prospective cohort study to assess gait quality parameters in 65 patients before and 1 year after primary unilateral TKA and their association with (changes in) PROMs scores. To determine whether gait quality parameters contain independent information on functional outcome after TKA in addition to PROMs, and to reduce the number of variables and statistical tests, a principal factor analysis was performed. The identified factors were classified as AP/VT gait quality, PROMs, Symmetry, and ML gait quality. The most representative variable for each factor was used to evaluate the postoperative results of the TKA and this showed significant improvements for all factors. Correlations between gait quality parameters on one hand and PROMs on the other hand were only weak to moderate.

Quality of gait was assessed using parameters that have been shown to adequately represent walking function in (elderly) populations (Rispens et al., 2014; Rispens et al., 2016). GS, HR and SR are indicators of gait symmetry, which has been described as being an important predictive factor for falling in knee OA patients and as one aspect of gait quality which can be improved by TKA (Moutzouri et al., 2017). The gait quality parameters measured in this study showed an increased gait quality one year postoperatively, which can be expected after TKA and concurs with previous work (Senden et al., 2011).

A principal axis factor analysis was performed to determine which factors underlie gait quality parameters and PROMs scores that were assessed in the present study. Since gait quality analysis provides researchers with a large number of different parameters, analyzing all these parameters individually could lead to type-1 errors and a potential source of bias. Using a factor analysis to group different parameters together allows researchers to limit the bias towards a type-1 error (Amboni et al., 2012; Hollman et al., 2011; Toebes et al., 2015). One interesting result was that all PROMs that were included in the final

Table 3
Rotated Factor Matrix with loading values for each parameter.

Parameter	Factor			
	1: AP/VT gait quality	2: PROMs	3: Symmetry	4: ML gait quality
Stride regularity VT	**−0.883**	*0.197*	*0.187*	*0.284*
Low frequency percentage AP < 0.7 Hz	**0.835**	*−0.137*	*−0.148*	*0.121*
Walking time 10 m	**0.808**	*−0.175*	*−0.233*	*0.119*
Low frequency percentage VT < 0.7 Hz	**0.754**	*−0.051*	*−0.179*	*0.133*
Stride time variability	**0.682**	*−0.251*	*−0.208*	*−0.012*
Gait smoothness (index of harmonicity) ML	**0.535**	*−0.089*	*−0.432*	*−0.034*
Stride regularity AP	**−0.475**	*0.196*	*0.152*	*0.405*
Gait smoothness (index of harmonicity) VT	**−0.452**	*0.171*	*0.008*	*−0.138*
Oxford knee score	*0.293*	**−0.922**	*−0.138*	*0.034*
KOOS QoL score	*−0.123*	**0.758**	*0.065*	*0.023*
KOOS sport & recreation score	*−0.106*	**0.610**	*−0.032*	*−0.220*
KOOS symptoms score	*−0.208*	**0.596**	*0.143*	*0.047*
EQ-5D	*−0.039*	**0.459**	*0.164*	*−0.076*
Gait symmetry (harmonic ratio) AP	*−0.234*	*0.143*	**0.787**	*−0.041*
Gait symmetry (harmonic ratio) VT	*−0.232*	*0.119*	**0.715**	*−0.057*
Gait symmetry (harmonic ratio) ML	*−0.099*	*0.111*	**0.623**	*0.177*
Stride regularity ML	*−0.481*	*0.097*	*0.062*	**0.784**
Low frequency percentage ML < 10 Hz	*0.246*	*−0.174*	*0.002*	**0.695**
Dominant frequency's amplitude ML	*0.204*	*−0.172*	*0.007*	**0.522**
Eigenvalues	6.543	2.452	1.891	1.611
% of variance represented by factor	23.620	14.250	10.479	9.347

VT = vertical; ML = mediolateral; AP = anteriorposterior; QoL = quality of life;KOOS = Knee Disability and Osteoarthritis Outcome Score. Bold = included in factor; italics = excluded from factor.

Table 4
This table shows the median values of the prominent variable of each factor.

Factor	Baseline	One year follow-up	*p*-value
AP/VT gait quality (stride regularity VT)	0.82 (0.15)	0.85 (0.12)	0.002
PROMs (OKS)	34 (10)	16 (9)	< 0.001
Symmetry (harmonic ratio AP)	2.36 (1.42)	2.72 (1.11)	0.044
ML gait quality (stride regularity ML)	0.64 (0.19)	0.69 (0.19)	0.028

Data in Median (IQR); VT = vertical; ML = mediolateral; AP = anteroposterior; PROMS = patient reported outcome measures; OKS = Oxford Knee Score.

factor analysis were grouped into a separate factor. This is an indication that PROMs assess a different aspect of functional outcome than gait accelerometry. This was further supported by at most weak to moderate correlations between gait quality parameters and PROMs. This lack of correlation might partially be due to PROMs scores being more correlated with pain than with functional performance (Stevens-Lapsley et al., 2011). PROMs, even though they have been repeatedly used to do so, appear not to reflect changes in function between before and after a TKA procedure adequately (Hossain et al., 2015; Naili et al., 2017). This suggests added value of objective performance measurements through trunk accelerometry besides using PROMs. Since accelerometers are being incorporated in modern electronics like smartphones and smart watches, these devices could potentially be used for knee OA and TKA patients in the future. This could provide physical therapists with information on which aspects of walking could be improved in individual patients, or be used by surgeons to evaluate preoperatively if a TKA is the right choice at that time for that particular patient.

There were several strengths to this study. The number of patients included was relatively large for a study evaluating gait quality and PROMs in TKA patients. Several frequently used PROMs were evaluated and patients were evaluated 1 year after surgery. The decision to include patients with differing levels of mobility (e.g. previous arthroplasties, use of walking aids) increased the external validity of the study, because the study population more accurately represented clinical orthopaedic practice. However, this heterogeneity could be considered a limitation to this study. It should be taken into account when analyzing the gait quality results that these measurements were performed in a clinical setting to provide patients with a setting in which they would be able to achieve the highest level of gait quality possible. It can be expected that patients walk differently when being monitored by a researcher, which can influence gait measurements (also known as the Hawthorne effect). A further limitation was that patients were measured in a clinical setting (as mentioned above) and gait parameters were calculated over only 2 × 50 meters of walking. Gait analysis has been proven to become more reliable when longer periods of ambulation are analyzed (van Schooten et al., 2014), and this would be a logical next step in research on the use of trunk accelerometry for assessing function before and after TKA. When patient's ambulation could be analyzed in their domestic setting in a less standardized and controlled environment, it may have a higher predictive value for actual functioning of patients after TKA. This would also allow quantity of walking to be assessed as well as quality, which might show a better

Table 5
This table shows the associations and *p*-values between the prominent variable of each gait quality factor and the prominent variable of the PROMs factor.

Spearman's rho (*p*-value)	PROMs (OKS)		
	Baseline	One year follow-up	Delta scores
VT/AP gait quality (stride regularity VT)	**−0.311 (0.012)**	−0.238 (0.060)	**−0.411 (0.001)**
Symmetry (harmonic ratio AP)	**−0.252 (0.043)**	**−0.270 (0.032)**	−0.071 (0.579)
ML gait quality (stride regularity ML)	−0.239 (0.055)	−0.015 (0.909)	**−0.350 (0.005)**

Bold = p-value 0.05 or lower. VT = vertical;ML = medial-lateral;AP = anterior-posterior; OKS = Oxford Knee Score.

correlation with patient satisfaction as reported in the PROMs.

5. Conclusions

Accelerometers were used to analyse gait quality in patients before and 1 year after primary unilateral TKA. Using a principal factor analysis, four factors were identified that represented AP/VT gait quality, PROMs, Symmetry, and ML gait quality. Correlations of gait quality parameters with PROMs were at most weak to moderate. This indicates that gait quality as assessed with accelerometers could provide additional and more detailed information on functional rehabilitation of TKA patients with objective quantifiable parameters, as a supplementary method to PROMs. Before trunk accelerometry can be used in clinical practice, further understanding of the relevance of gait quality measurements presented in this study for functioning in daily life knee OA patients is needed.

CRediT authorship contribution statement

Bas L. Fransen:Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing.**Nina M.C. Mathijssen**:Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing.**Karin Slot**:Data curation, Investigation, Writing - original draft, Writing - review & editing.**Nicole H.H. de Esch**:Data curation, Investigation, Writing - original draft, Writing - review & editing.**Hennie Verburg**:Data curation, Investigation, Supervision, Validation, Writing - original draft, Writing - review & editing.**Olivier P.P. Temmerman**:Data curation, Investigation, Supervision, Validation, Writing - original draft, Writing - review & editing.**Marco J.M. Hoozemans**:Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing - original draft, Writing - review & editing.**Jaap H. van Dieën**:Formal analysis, Methodology, Supervision, Validation, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The institution of one or more of the authors has received funding from Zimmer Biomet, Mahwah, U.S.A. They did not play a role in study design; in the collection, analysis and interpretation of data; in the writing of the report; and/or in the decision to submit the article for publication.

Appendix A. Supplementary data

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