"Measuring gait patterns using wearable inertial sensors in a population of knee arthroplasty patients participating in a double-blinded randomized controlled trial, mUKA vs. TKA."

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Abstract

Rationale and purpose: Recent technological achievements have made advanced gait analysis using inertial sensors possible. Previous studies have shown that inertial sensors can be reliably used to measure gait in patients suffering from osteoarthritis (OA) of the knee and patients with either total (TKA) or unicompartmental (UKA) knee arthroplasty. It has been a general perspective of several studies to use this technology to clinically assess knee status before and after knee joint replacement. The purpose of this study is to investigate the gait patterns in a population of knee arthroplasty patients participating in a double-blinded RCT study, mUKA (medial UKA) vs. TKA, before and 4 months after surgery.

Our objectives are:

1. Investigate pre- and postoperative differences of gait-patterns at level and uphill walking in a laboratory setting.
2. Investigate differences of gait-patterns between total knee arthroplasty patients (TKA) and medial unicompartmental knee arthroplasty patients (mUKA).

Methods: 14 patients were included prospectively. They had all been diagnosed with isolated antero-medial OA and participated in “mUKA vs TKA”. 7 were randomized to receive UKA and 7 to receive TKA. The participants’ gait was examined before surgery and 4 months after knee joint replacement. Participants’ gait was examined at level and uphill walking at their self-determined comfortable speed and self-determined maximal speed. Examination was done using wearable inertial motion sensors. Data was analyzed in R, using our own algorithm. Average gait cycles were produced, and 36 gait-parameters were defined. We used non-parametric Wilcoxon- and Mann-Whitney U-test to identify inter- and intra-participant variance. Due to our relatively low number of participants, and the explorative nature of this study, a p-value of < 0.1 was considered significant.

Results: We found the greatest differences in gait between the pre- and postoperative group, at the level-walking-comfortable-speed-setting. Improvements of gait were seen in categories such as spatiotemporal, angular, angular velocity, angular acceleration and variability of gait parameters. When comparing UKA’s and TKA’s we found the greatest differences in uphill walking at maximal speed. In this setting, 10 of 36 parameters were significantly different. UKA’s had greater improvements in all categories.

Conclusion: We found a postoperative improvement in gait four months after knee-replacement in our study group. Uphill walking seemed to highlight differences between the gait of UKA’s and TKA’s. Our findings strengthened the findings of previous studies: that UKA’s recover an improved gait-pattern faster than TKA’s. Further studies with greater numbers of participants are needed to confirm our results and to investigate gait differences 1 year postoperatively.

Resumé

Rationale og formål: Nylige teknologiske udviklinger har gjort kvantitativ bestemmelse af bevægelsesmønstre mulige. Tidligere studier har vist at bevægelsessensorer kan bruges pålideligt, til at bestemme bevægelsesmønstre af patienter med knæ-artrose, og patienter med indsat knæ-alloplastik. Det har været et gennemgående perspektiv i flere studier at bruge denne teknologi til at kvantificere artrose-patienters knæ-status før og efter indsættelse af knæ-alloplastik. Formålet med dette studie var at bestemme præ- og postoperative bevægelsesmønstre i en population af patienter, der deltog i et dobbelt-blindet RCT studie, ”mUKA vs. TKA”.

Vores formål var:

1. At undersøge de præ- og postoperative bevægelsesmønstre ved flad og opadgående gang ved test i laboratorium.
2. At undersøge forskelle i bevægelsesmønstre mellem patienter der fik indsat en total knæ-alloplastik (TKA) og patienter der fik indsat en medial unikompartmental knæ-alloplastik (UKA).

*Metode:*14 patienter blev inkluderet. Alle patienter var diagnosticeret med antero-medial knæ-artrose og deltog i ”mUKA vs. TKA”. 7 fik indsat UKA og 7 fik indsat TKA. Deltagerne blev undersøgt én gang før operation og 4 måneder efter indsættelse af alloplastik. Deltagerne blev undersøgt ved flad og opadgående gang, ved selv-bestemte komfortable og maximale hastigheder. Undersøgelsen blev udført vha. bærbare bevægelsessensorer. Data blev analyseret i R med vores egen algoritme. Gennemsnitlig gang-cyklus blev skabt ud fra data og 36 gang-mønster-parametre blev udregnet. Vi anvendte de non-parametriske tests Wilcoxon og Mann-Whitney U-test til at identificere forskelle mellem målinger. Grundet vores relative lave antal af forsøgsdeltagere, blev et signifikansniveau på 0,1 defineret.

Resultater: Vi fandt de største forskelle mellem de præ- og postoperative målinger ved flad gang og komfortabel hastighed. 16 ud af 36 parametre var signifikant anderledes efter indsættelse af alloplastik. Forbedringer blev set i spatiotemporale-, vinkel-, vinkelhastighed-, vinkelacceleration- og variabilitetsparametre. Da vi sammenlignede UKA’er med TKA’er fandt vi de største forskelle ved opadgående gang med maximal hastighed. I denne indstilling fandt vi at 10 ud af 36 parametre var signifikant anderledes. UKA’erne var signifikant bedre end TKA’erne i spatiotemporale-, vinkel-, vinkelhastighed-, vinkelacceleration- og variabilitetsparametre.

Konklusion: En tydelig postoperativ forbedring af bevægelsesmønstre blev detekteret fire måneder efter indsættelse af knæ-alloplastik. Opadgående gang tydeliggjorde forskelle mellem UKA’er og TKA’er. Vores fund styrkede tidligere studiers konklusion: at UKA’er udvikler et bedre bevægelsesmønster hurtigere end TKA’er. Flere studier er nødvendige for at bekræfte vores fund og for at undersøge bevægelsesmønstre 1 år postoperativt.

Introduction

Over the past five decades increasing age and obesity in the general population have led to a global rise in incidence and prevalence of knee osteoarthritis (OA) [1-3]. When conservative treatment has failed, knee joint replacement is considered a safe and effective treatment for end-stage OA. In Denmark, 8.584 knee joint replacement surgeries were performed in 2017 alone [4]. The decision to perform knee joint replacement is based on patient history, radiographic findings, and passive range of motion (pROM) [2]. Previous studies have shown that patient-reported outcome measures, range of motion (ROM) at discharge, and gait analysis can be used to strengthen the decision for surgery or conservative treatment as well as evaluating a patient's postoperative status [5-12].

The "gold standard"-method for gait analysis is considered to be advanced motion camera technology, force plates and optoelectric methods [10, 13-16]. These systems require a stationary laboratory, trained and specialized personnel, and are expensive (estimated at around 17.000 USD) [10, 17]. Mobile gait analysis systems provide an opportunity to overcome these inconveniences, as they are relatively cheap (hardware-cost is estimated at around 1200 USD) and easy to use [6]. These systems often consist of a combination of accelerometers, gyroscopes and magnetometers and are named inertial sensors [18]. Accelerometers and gyroscopes measure acceleration and positioning to calculate joint angles. The magnetometer can be included in an inertial sensor, because it overcomes some of the disadvantages of only using accelerometers and gyroscopes, such as drift-errors: (small errors in measurement of acceleration results in greater errors when calculating velocity and then even greater errors when calculating positioning) [18]. An inertial sensor that includes a magnetometer however, is vulnerable to magnetic materials. Several studies have validated the use of inertial sensors when comparing them to motion camera technology, force plates and other optoelectric methods [10, 13, 15, 17, 19-21]. These methods are considered valid and reliable but have varied values of reported accuracy of measured knee angle (+/- 5 degrees) [18, 22]. Our method has previously been validated, and it was demonstrated to have excellent reproducibility with an ICC between 0.85 and 0.98, and 95 % limits of agreement for knee angle at [-6.5 : 5.5] [23]. Our findings from our validation study were consistent with findings from the above-mentioned studies [18, 22].

Previous studies have reported a variety of different outcome parameters in gait analysis, and a consensus regarding relevant outcome measures does not seem to exist [18]. The most often reported outcome parameters, that change after surgery, are knee angle and spatiotemporal parameters, such as stride frequency, stride duration, cadence, walking speed [6, 18]. Calliess et al. reported a postoperative reduction of maximum acceleration in the knee joint when patients performed a start-to-run test [6]. They also found that the power of deceleration increased in all postoperative patients and that an increase in knee flexion at heel strike while descending stairs were found. Rahman et al. found that the most obvious difference between patients with OA and patients 1 year after TKR were knee sagittal range of motion during the swing phase and stance phase [24]. Yakhdani et al. reported that patients with osteoarthritis had less variability than healthy controls [7]. Yakhdani et al. hypothesized that the standard deviation of the angular velocity could act as a parameter for knee variability and stability. They hypothesized that this was a coping strategy for preventing instability of the knee joint [7]. This finding could indicate that variability is an important measure when evaluating the gait of OA patients. Wiik et al. reported that gait differences in spatiotemporal parameters between healthy controls and OA patients were more easily detected at downhill walking than level walking [25]. Wiik et al. also demonstrated that differences in gait between UKA's and TKA's were clearer at downhill walking. The previous studies concerning gait analysis of OA patients and knee replacement patients are unclear about which parameters are the most relevant to examine. We investigated if the same changes in outcome parameters, that were seen in the abovementioned studies, were present in our results and if uphill walking would differentiate between UKA's and TKA's in the same manner as downhill walking. It was our hypothesis that angular velocity and acceleration would be the most indicative of knee-joint-status, because patients with pain or instability of the knee probably have less control of their knee [6, 7]. The standard deviations of many gait parameters were included as separate parameters, because they might be a measure of variability of gait [7]. We present in this study a new method for analyzing data produced by the sensors and many new unreported outcome parameters.

Objectives

1. Investigate pre- and postoperative differences of gait-patterns, at level and uphill walking in a laboratory setting.
2. Investigate differences of gait-patterns between total knee arthroplasty patients (TKA) and medial unicompartmental knee arthroplasty patients (mUKA).

Materials and methods

All patients, included from March 2018 to November 2018 in the mUKA vs. TKA RCT, were offered participation in this study. The mUKA vs. TKA study is a double-blinded randomized controlled trial. Only patients with confirmed anteromedial arthrosis (AMOA) are included and participants are randomized in the OR to receive either UKA or TKA. Patients are informed of the inserted prosthesis-type at the 1-year postoperative control. The study is a multicenter-study with five including hospitals (Gentofte, Næstved, Århus, Farsø, Vejle). Only patients admitted to Gentofte Hospital were included for the present gait-analysis study. Patients were screened based on the exclusion and inclusion criteria included in the mUKA vs. TKA study [26]. The criteria are as follows:

Inclusion criteria:

OA that is so severe that arthroplasty is justified. The etiology of the arthrosis in this context is irrelevant. The diagnosis is ensured by:

- Standard X-ray studies with PA, lateral, and skyline projections.

- Clinical investigation: Patient history, clinical examination and X-ray projections should speak for AMOA. The prerequisite for surgery is a stable joint, a correctable varus deformity and flexion to at least 110 ° and minimal lateral compartment damage.
- Normal TF-stability
- Lack of effect of conservative treatment. The patient should have attempted conservative treatment in the form of weight loss (if applicable), medical treatment with NSAIDs or analgesics. Physical therapy may also be attempted, but this is not a requirement for inclusion.

Exclusion criteria

- Non-Danish citizenship.
- Minors and persons under 18 years.
- Senile dementia.
- Insufficient Danish language capabilities.
- Severe psychiatric disorder.
- Alcoholism or drug abuse.
- Disseminated malignancy.
- Severe systemic disease (eg hemiparesis, severe parkinsonism).
- Rheumatoid arthritis.
- Employed at one of the participating orthopedic surgery departments.

The following knee -specific exclusion criteria:

- Sagittal or coronal instability.
- Intraoperative diagnosis of significant tibiofemoral arthritis laterally or patellofemorally.
- Recent knee-trauma
- Complex regional pain syndrome.
- Arthrofibrosis.
- Extension defect (more than 10 degrees).
- Flexion defect with less than 110 degrees of flexion.
- Skyline: lateral subluxation or bone-on-bone visualized.

[26]

Additional exclusion criteria were: Serious cardiovascular disease and serious neurological disease which might affect gait. Patients were included after inclusion in the mUKA vs. TKA. They received oral information and were given written information at least one day before preoperative measurement.

Between March and November 2018, 20 patients were included in mUKA vs. TKA at Gentofte Orthopedic department. 2 patients declined participation in preoperative gait measurement before knee joint replacement and 1 patient declined to participate in the postoperative measurement. 2 patients were measured preoperatively but did not receive a knee-replacement in our study period. 1 patient was excluded, due to faulty pre-operative data-recording. A total of 14 patients with pre- and postoperative measurements were included in our study. 7 were randomized to receive UKA and 7 to receive TKA. The participants were measured once preoperatively (mean of 16 days before surgery) and once postoperatively (mean of 123 days after surgery).

We used the same instructions that were used in the validation study of the sensors [23]. The participant was equipped with 2 sensor units. The inertial sensors and smartphone which controls them, were provided by ICURA Aps (ISENS-100, Icura Aps, Copenhagen, Denmark). The sensors consist of an accelerometer, gyroscope and magnetometer. One sensor is placed 10 cm distal of the trochanter major and the other just above the lateral malleolus (**figure 1**). The sensors continually measure the knee-angle with a nominal frequency of 20 Hz. The sensor weighs 27 grams and sizes 68x42x15 mm. The sensors were calibrated twice before measuring started. First, the sensors performed self-calibration through the software sensor-systems provided by Icura. Second, the sensors were manually calibrated, measuring and noting the value of maximal extension, i.e. the knee-angle of the patient’s stretched knee, into the controlling smart-phone. Ioban tape from 3M were used, to secure placement of the sensor (6648EZ, 3M, Maplewood, MN). The sensors are connected to the smartphone via. Bluetooth. The smartphone controls the sensors by using a custom-made app called “knee angle”.

Figure 1: Wearable sensors placement on the leg attached with Ioban.

The examination took place on a treadmill. After a 6 minute acclimatization period on the treadmill at level walking [27], all participants walked as follows:

1) 2 minutes at their self-determined comfortable speed.
2) 1 minute at their self-determined maximal speed.
3) The treadmill was set to 7 degrees inclination.
4) The patient was again instructed to walk 2 minutes at their self-determined comfortable speed.
5) Then 1 minute at their self-determined maximal speed.

Start and end times were noted including walking speed. When the examination was finished, data was uploaded to an FTP-server. Data contained timestamp and knee-angle.

Method of data analysis.

The following is a description of our data analysis. We used the program "R".

1) Data-sheet for one patient in one setting, containing timestamp and angle values, is loaded from working directory. Angle values above 160 degrees and below -20 degrees are filtered.
2) Step frequency based on spectral analysis on unevenly sampled data is performed (the Lomb-Scargle algorithm).
3) A search for peaks and troughs was based on the period determined by the step frequency and fitting of a second-degree polynomial to the sample neighborhood of maximum and minimum angles (**figure 2**).

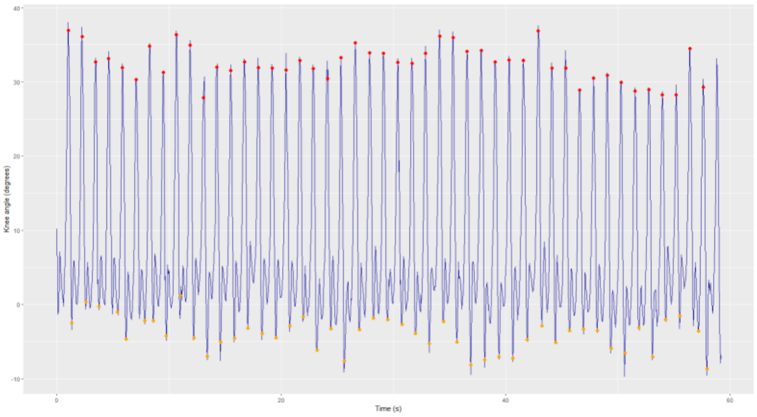


Figure 2: showing identified peaks and troughs over 60 seconds.

4) All gait cycles were resampled, so that an equal number of data points were used in all cycles. We used linear interpolation and upsampling.
5) A Fourier expansion is used to "fit" raw data. This was done to create a mathematical function, based on a sine-cosine form, which allowed differentiation of the curve. In this way, values of angular velocity and acceleration were extrapolated. Following equation was used:

Fourier series, sine-cosine form

$$s_N(x) = a_0/2 + \sum_{n=1}^{N} \left(a_n \cos\left(\frac{2\pi n x}{P}\right) + b_n \sin\left(\frac{2\pi n x}{P}\right) \right). \qquad \textbf{(Eq.2)}$$

Number of Fourier elements was 10 (N = 10).

6) 20 average gait parameters were calculated from the Fourier series. Bootstrapping of 15 samples, a type of resampling with replacement, was used to calculate 16 standard deviations of their corresponding parameter. In addition, following graphs were produced:

   a. An average gait cycle with knee-angle as a function of time [a]. (see **Appendix 2** for example of a gait cycle graph).
   b. Angular velocity (the derivative of the knee-angle function)
   c. Angular acceleration (the derivative of the angular velocity function)

7) The 36 produced parameters are listed and categorized as follows:

Category	**Parameter.**	**Description.**	**Variability**
Spatiotemporal			
	Step frequency.	Frequency of steps (1/steps).	
	Step-period	Step-duration (in seconds).	
	Steps	No. of steps.	
	Walking Speed.	The speed with which the patient is walking (m/s).	
Angular			
	Amplitude (gait-ROM, or gROM)[c]	Difference between maximal and minimal angle measured (in degrees).	SD Of the Amplitude
	Minimal angle.	Smallest value of measured angles.	SD Of the Minimal angle
	Maximal angle.	Largest value of measured angles.	SD Of the Maximal angle
	Position of Minimal angle.	The time at which the minimal angle is found in the gait cycle (in radians) [a].	SD Of Position of Minimal angle
	Position of Maximal angle.	The time at which the maximal angle is found in the gait cycle (in radians) [a].	SD Of Position of Maximal angle
	AUC	Area under the average gait cycle curve.	SD of AUC.
Angular Velocity			
	Minimal angle velocity.	Lowest value of angle-velocity measured during the gait cycle (angles/radian).	SD of Minimal angle velocity.
	Maximal angle velocity.	Highest value of angle-velocity during the gait cycle (angles/radian).	SD of Maximal angle velocity.
	Position of Minimal angle velocity.	The time at which the minimal angular velocity is found in the gait cycle (in radians) [a].	SD of Position of Minimal angle velocity.
	Position of Maximal angle velocity.	The time at which the maximal angular velocity is found in the gait cycle (in radians) [a].	SD of Position of Maximal angle velocity.
Angular Acceleration			
	Maximal acceleration in swing-phase.	Maximal angle-acceleration during the swing-phase [b] (angles/radian^2).	SD of Maximal acceleration in swing-phase.
	Minimal acceleration in swing-phase.	Minimal angle-acceleration during the swing-phase [b] (angles/radian^2).	SD of Minimal acceleration in swing-phase.
	Maximal acceleration in stance-phase	Maximal angle-acceleration during the stance phase [b].	SD of Maximal acceleration in stance-phase.
	Position of Maximal acceleration in swing-phase.	The time at which the maximal acceleration in the swing phase is found in the gait cycle (in radians) [a].	SD of Position of Maximal acceleration in swing-phase.
	Position of Minimal acceleration in swing-phase.	The time at which the minimal acceleration in the swing phase is found in the gait cycle (in radians) [a].	SD of Position of Minimal acceleration in swing-phase.
	Position of Maximal acceleration in swing-phase.	The time at which the maximal acceleration in the stance phase is found in the gait cycle (in radians) [a].	SD of Position of Maximal acceleration in swing-phase

[a] the period of a full gait cycle is expressed as $2 \cdot \pi$.

[b] Swing and stance phases are defined as **figure 3 illustrates**:

[c] Gait-ROM is introduced here as a parameter, and is defined as the amplitude of the gait cycle. It is a relevant parameter to examine, because it is a measure of mobility and knee flexion and extension.

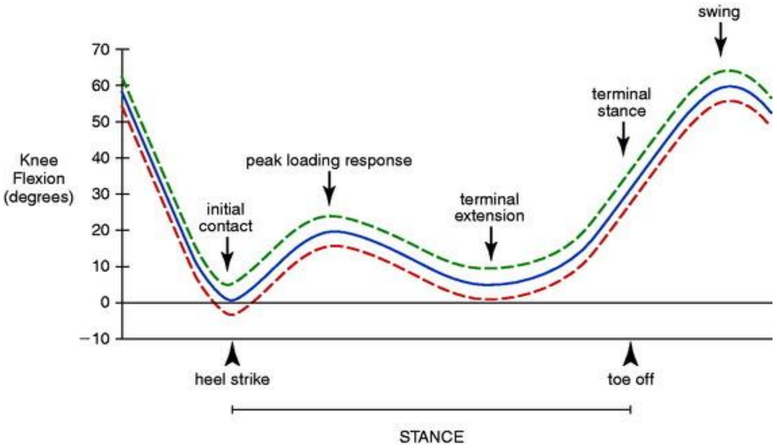


Figure 3. [28]

The standard deviations of all parameters (except spatiotemporal parameters) were calculated, and included as separate parameters, because we hypothesized that they represent variability in gait.

For statistical analysis, Excel (Windows 8) and SPSS was used. The means of all parameters were calculated. Because of our small sample size (n = 14), and because our data was paired, we used the non-parametric Wilcoxon test to compare means of the preoperative measurements with the means of the postoperative measurements. To compare UKA's and TKA's we used the non-parametric and non-paired test, the Mann-Whitney U-test. A p-value of 0.1 was considered significant, due to our small sample size, and because of the exploratory nature of our study

Results

Patient demographic is shown in **Table 1**:

	UKA (n = 7)	TKA (n = 7)
Gender (M:F)	6:1	5:2
Age (years)	67.71 +/- 5.59	68.14 +/- 8.53
BMI	26.38 +/- 3.49	27.12 +/- 4.68
Height (m)	1.74 +/- 0.08	1.78 +/- 0.11
The values are indicated as mean +/- SD Non-parametric Wilcoxon test demonstrated no significant differences between the groups (p>0.05).		

Table 2 lists the values of parameters measured before and after surgery. Only parameters that were found to be significantly different after surgery were included and only some parameters are illustrated. All

calculated test-data is listed in **Appendix 1**. Gait cycles for one patient, in one setting before and after surgery is shown in **Appendix 2.**

Table 2

n = 14	**Parameter**	**Before**	**After**	**p-value**
Level walking, comfortable speed				
Spatiotemporal	Step frequency (1/steps)	0.69	0.78	<0.00
	Step-period (seconds)	1.46	1.34	0.02
	Steps	80.00	90.79	<0.00
	Walking speed (m/s)	2.23	3.03	0.01
Angular	Amplitude (degrees)	37.46	45.48	0.05
	SD of Maximal angle (degrees)	1.93	1.31	0.02
	Position of Minimal angle (radians)	2.75	2.08	0.06
	SD of Position of Minimal angle (radians)	0.53	0.11	<0.00
	AUC	78.46	109.36	0.01
Angle velocity	Minimal angle velocity (degrees/radian)	-34.70	-41.49	0.07
	SD of Maximal angle velocity (degrees/radian)	8.11	5.57	0.01
	Position of Minimal angle velocity (radians)	0.71	0.94	0.04
Angle acceleration	SD of Maximal acceleration in swing-phase (degrees/radian^2)	40.56	25.40	0.06
	Maximal acceleration in stance-phase (degrees/radian^2)	68.40	104.96	0.03
	Position of Maximal acceleration in stance-phase (radians)	1.11	1.29	0.05
	SD of Position of Maximal acceleration in stance-phase (radians)	0.44	0.23	0.07
Level walking, maximal speed				
Spatiotemporal	Step frequency (1/steps)	0.83	0.89	0.02
	Steps	47.21	51.07	0.01
	Walking speed (m/s)	3.56	4.41	<0.00
Angular	SD of Position of Minimal angle (radians)	0.82	0.11	0.08
	AUC	90.53	124.15	0.06
Angle velocity	Position of Minimal angle velocity (radians)	0.72	1.13	<0.00
Angle acceleration	Position of Maximal acceleration in stance-phase (radians)	1.24	1.42	0.02
7 degrees inclination, comfortable speed				
Spatiotemporal	Step frequency (1/steps)	0.73	0.83	<0.00
	Step-period (seconds)	1.38	1.19	0.01
	Steps	82.71	96.36	<0.00
	Walking speed (m/s)	2.59	3.44	<0.00
Angular	SD of Minimal angle (degrees)	1.47	2.25	0.05
	SD of Maximal angle (degrees)	1.64	1.99	0.07
Angle velocity	SD of Minimal angle velocity (degrees/radian)	5.80	8.15	0.07
	Position of Minimal angle velocity (radians)	0.61	0.84	0.01
Angle acceleration	SD of Position of Minimal acceleration in swing-phase (radians)	0.35	1.14	0.03
	Position of Maximal acceleration in stance-phase (radians)	1.09	1.41	<0.00
7 degrees inclination, maximal speed				
Angle velocity	Position of Minimal angle velocity (radians)	0.67	0.92	0.01
Angle acceleration	Maximal acceleration in swing-phase (degrees/radian^2)	76.07	59.79	0.06
	Position of Maximal acceleration in stance-phase (radians)	1.18	1.44	0.01

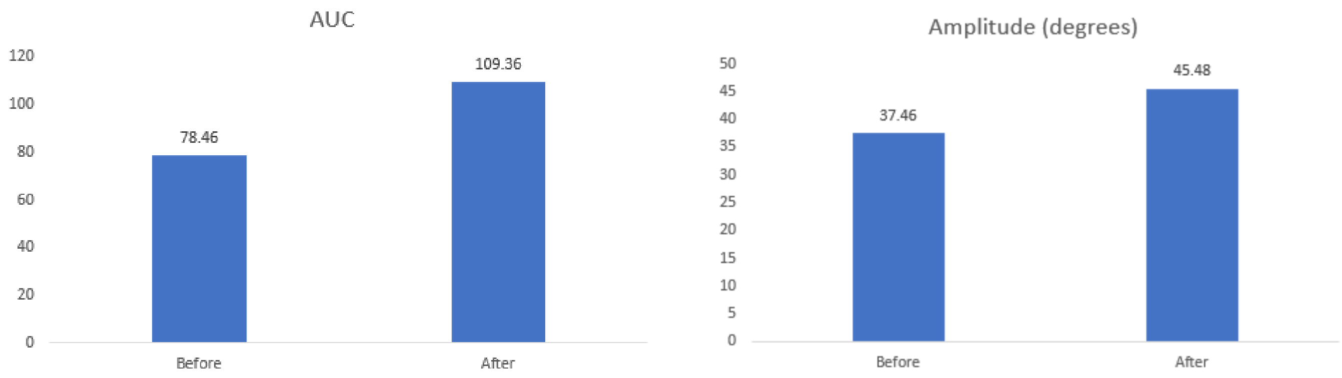
<u>Level walking, at self-determined comfortable speed.</u>

The greatest differences in gait before and after surgery were seen at comfortable speed, level walking. Only these results are discussed further. At this setting 16 of 36 parameters were significantly different after surgery.

Patients walked faster after knee-replacement: **Step frequency (1/steps)** increased from 0.69 to 0.78 (p = <0.00) and **step-period** decreased from 1.46 to 1.34 seconds (p = 0.02). N**o. of steps** increased from 80 to 90.79 (p = <0.00) and **walking speed** also increased from 2.23 to 3.03 m/s (p = 0.01).

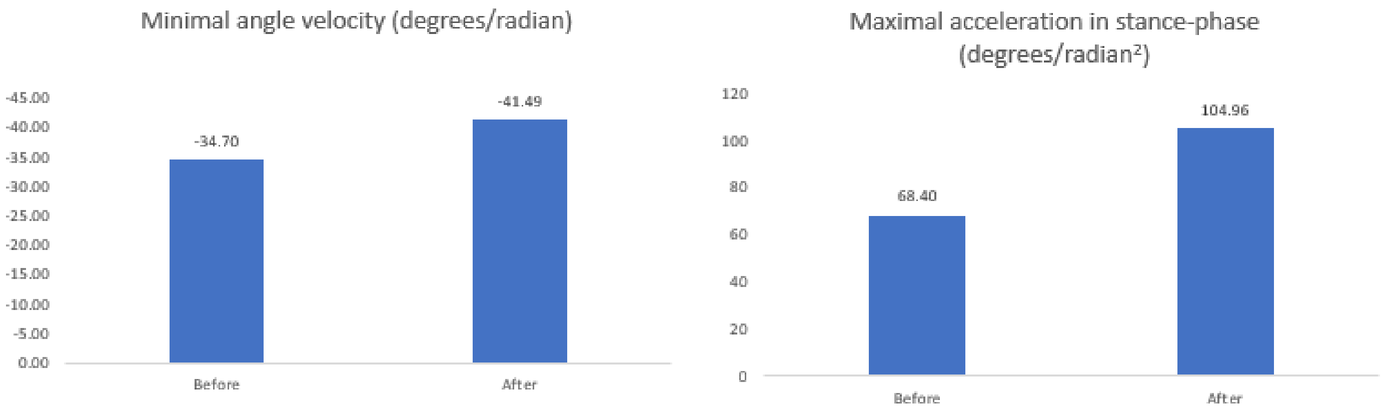
Patients had greater gROM 4 months after surgery and they had better mobility. **Area under the curve (AUC)** increased from 78.46 to 109.36 (p = 0.01) (**Figure 4**). **Amplitude or gROM** increased from 37.46 to 45.48 degrees after surgery (p = 0.05) (**Figure 5**).

Figure 4 and 5.



There was an absolute increase of angle velocity and acceleration, maybe because patients had greater control of the knee joint. The absolute value of **Minimal angle velocity** increased from -34.70 to -41.49 angles/radian after surgery (p = 0.07) (**Figure 6)**. It is noted here as a negative value, because the knee is extending, and is therefore opposite to knee-flexion. **Maximal acceleration during stance phase** increased from 68.40 to 104.96 angles/radian^2 (p = 0.03) (**Figure 7)**.

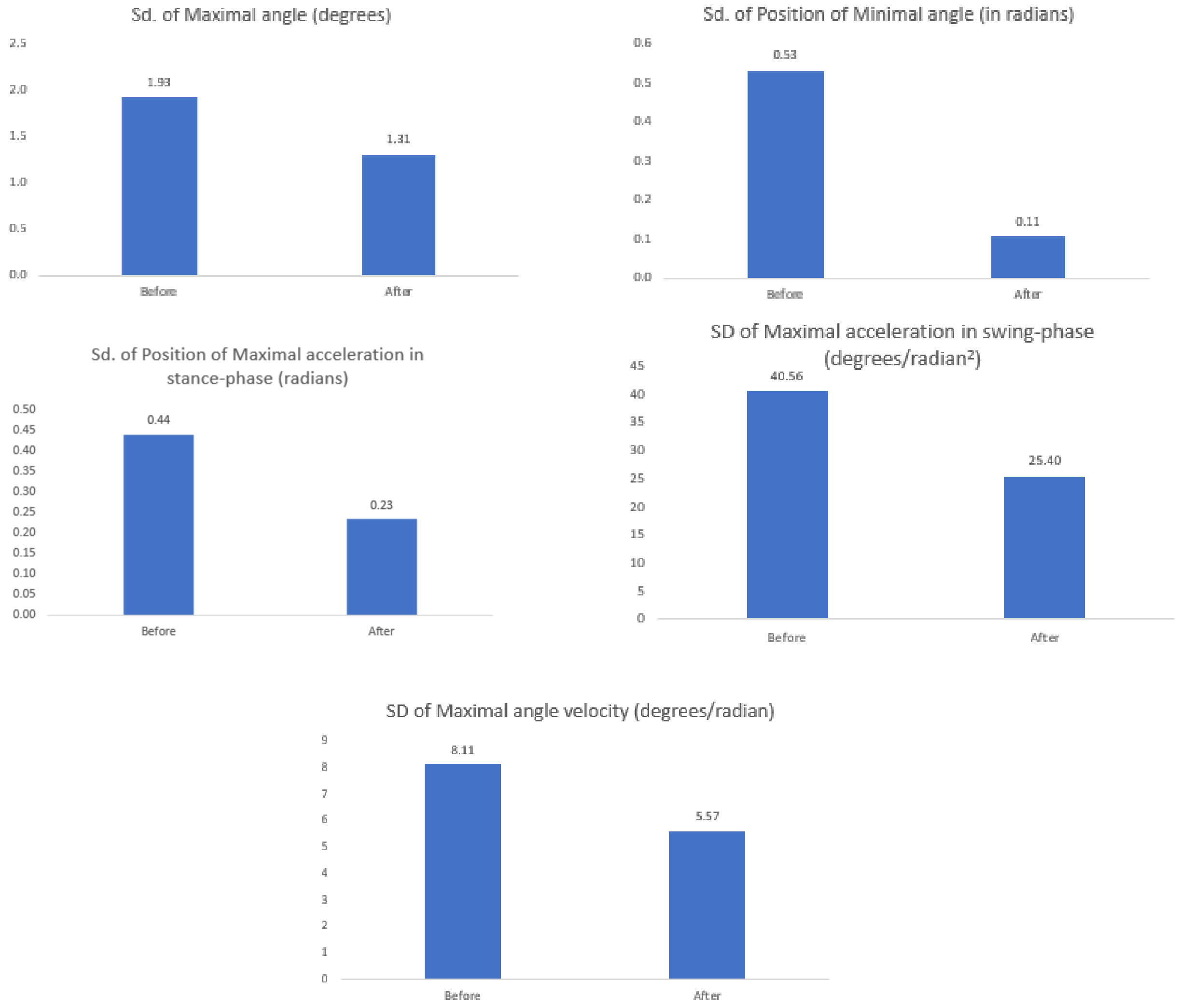
Figure 6 and 7.



Timing of gait-cycle-events also changed. **Position of Minimal angle** decreased from 2.75 to 2.08 radians (p = 0.06) meaning that full extension of the knee occurred sooner in the gait cycle. **Position of Minimal angle velocity** increased from 0.71 to 0.94 radians meaning that the maximal velocity of extension occurred later in the gait cycle (p = 0.04). **Position of Maximal acceleration during stance-phase** also increased from 1.11 to 1.29 radians (p = 0.05), suggesting that stance-phase occurred later in the gait cycle.

5 variability parameters decreased significantly, suggesting that variability of gait decreased after surgery (**Figure 8-12**). **SD of Maximal angle** decreased from 1.93 to 1.31 degrees (p = 0.02). **SD of Position of Minimal angle** decreased from 0.53 to 0.11 degrees (p = <0.00). **SD of Maximal speed** decreased from 8.11 to 5.57 angles/radian (p = 0.01). **SD of Maximal acceleration in swing-phase** decreased from 40.56 to 25.40 angles/radian^2 (p-value = 0.06). **SD of Position of Maximal acceleration in stance-phase** decreased from 0.44 to 0.23 angles/radian^2 (p-value = 0.07).

Figure 8 to 12.



We compared TKA's with UKA's. Significant differences are listed in **Table 3**

Table 3

Level walking, comfortable speed	**Parameter**	**After TKA (n = 7)**	**After UKA (n = 7)**	**p-value**
Angular	SD of Position of Minimal angle (radians)	0.14	0.08	0.02
Angle acceleration	SD of Maximal acceleration during stance-phase (angles/radian^2)	29.70	44.30	0.06
	The Position of Maximal acceleration during swing-phase (radians)	1.10	1.48	0.09
Level walking, maximal speed				
Spatiotemporal	Step frequency (1/steps)	0.81	0.96	0.05
	Step-period (seconds)	1.28	0.99	0.05
	Steps	46.29	55.86	0.03
	Walking speed (m/s)	3.69	5.14	0.03
Angle velocity	SD of Minimal angle velocity (degrees/radian)	5.47	9.58	0.09
	Maximal angle velocity (degrees/radian)	43.74	41.66	0.05
Angle acceleration	Position of Maximal acceleration during swing-phase (radians)	1.20	1.63	0.01
7 degrees inclination, comfortable speed				
Spatiotemporal	Walking speed (m/s)	2.89	4.00	0.03
Angular	Position of Minimal angle (radians)	3.60	2.38	0.06
	SD of Position of Minimal angle (radians)	0.80	0.12	0.02
Angle velocity	SD Of Maximal angle velocity (degrees/radian)	5.48	7.42	0.06
	Position of Minimal angle velocity (radians)	0.75	0.94	0.09
Angle acceleration	Position of Maximal acceleration in stance-phase (radians)	1.29	1.53	0.09
7 degrees inclination, maximal speed				
Spatiotemporal	Step frequency (1/steps)	0.82	0.95	0.05
	Step-period (seconds)	1.23	1.00	0.05
	Steps	46.57	54.29	0.04
	Walking speed (m/s)	3.60	4.84	0.05
Angular	SD of Position of Minimal angle (radians)	0.84	0.09	0.05
	AUC	87.00	118.95	0.09
Angle velocity	Minimal angle velocity (degrees/radian)	-31.80	-41.44	0.06
	SD of Minimal angle velocity (degrees/radian)	4.53	6.88	0.03
Angle acceleration	Maximal acceleration in stance-phase (degrees/radian^2)	72.00	107.37	0.09
	Position of Maximal acceleration in stance-phase (radians)	1.33	1.55	0.07

Uphill walking, at maximal speed.

The greatest differences in gait when comparing UKA’s with TKA’s were seen at maximal speed, uphill walking. Only these results are discussed further. At this setting 10 of 36 parameters were significantly different after surgery.

UKA’s walked faster than UKA’s: **Step frequency** was 0.82 for TKA’s and 0.95 for UKA’s (p = 0.05) **(Figure 13)**. **Step-period** was 1.23 for TKA’s and 1.00 for UKA’s (p = 0.05). **No. of steps** was 46.57 for TKA’s and 54.29 for UKA’s (p = 0.04) **(Figure 14)**. **Walking speed** was 3.60 for TKA’s and 4.84 for UKA’s (p = 0.05) **(Figure 15)**.

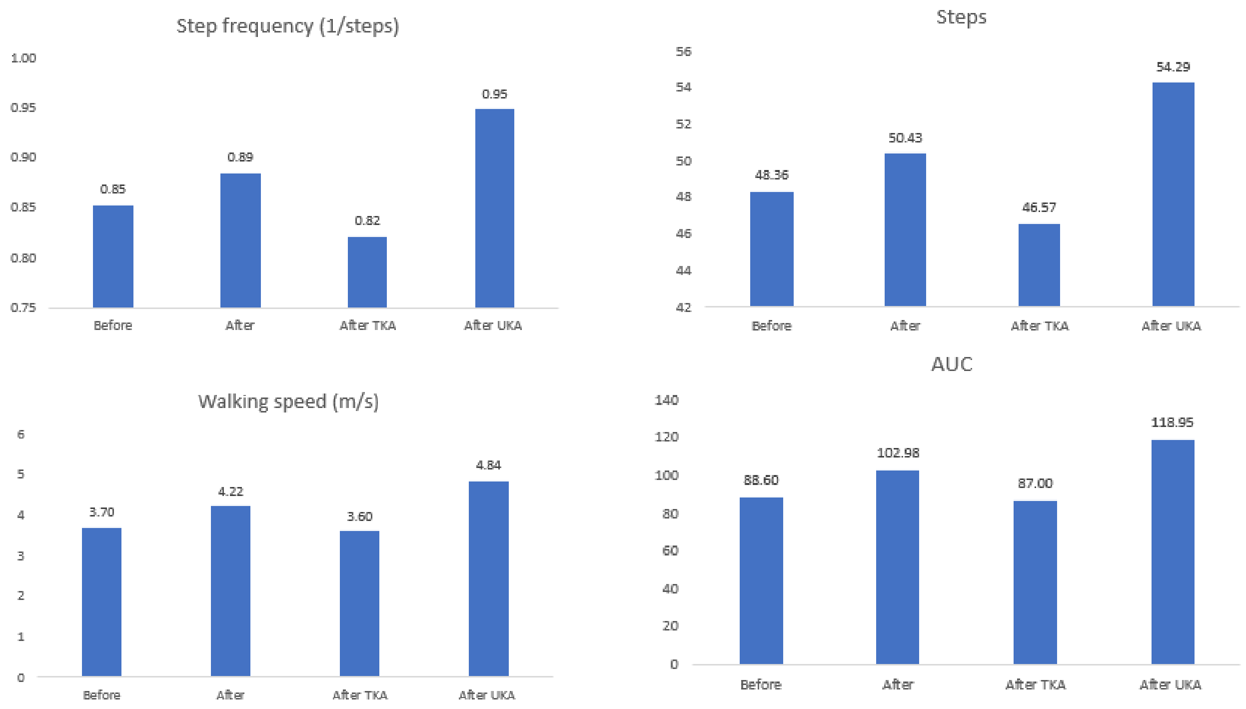
UKA’s had greater mobility than TKA’s: **Area under the curve** was 87.00 for TKA’s and 118.95 for UKA’s (p = 0.09) **(Figure 16)**.

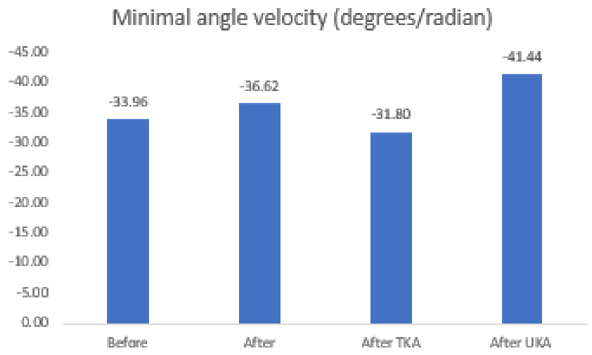
UKA’s had greater absolute values of angle velocity and acceleration, maybe because they had better control of their swing. **Minimal angle velocity** was -31.80 for TKA’s and -41.44 for UKA’s (p = 0.06) **(Figure 17)**. **Maximal acceleration in stance-phase** was 72.00 for TKA’s and 107.37 for UKA’s (p = 0.09) **(Figure 18)**.

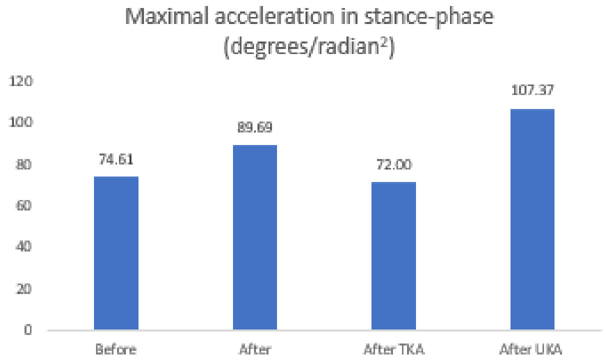
Timing of gait-cycle events was different: **Position of Maximal acceleration in stance-phase** was 1.33 for TKA’s and 1.55 for UKA’s (p = 0.07), meaning stance-phase occurred later in the gait cycle.

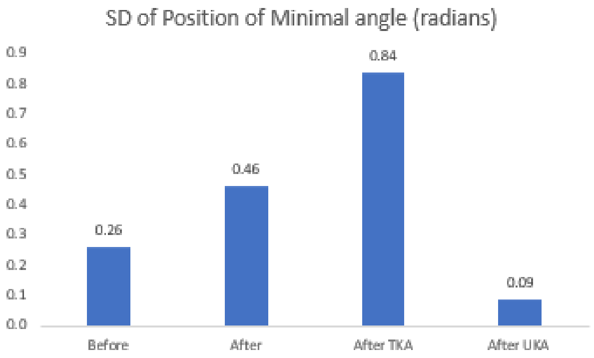
Variability were greater for TKA’s regarding the position of full extension, but variability were greater for UKA’s regarding Minimal angle velocity. **SD of Position of Minimal angle** was 0.84 for TKA’s and 0.09 for UKA’s (p = 0.05) **(Figure 19)**. **SD of Minimal angle velocity** was 4.53 for TKA’s and 6.88 for UKA’s (p = 0.03) **(Figure 20)**.

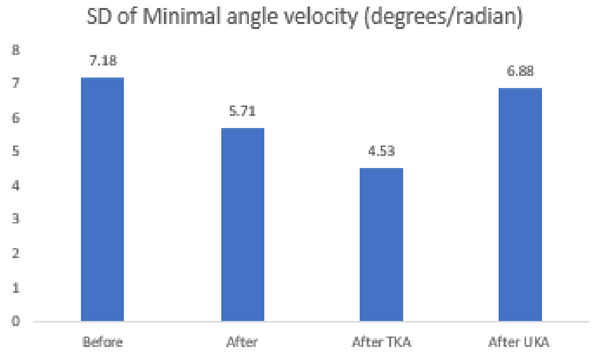
Figure 13 to 20.











Discussion

Before vs. after knee joint replacement:

The goal of this study was to investigate gait differences measured before and after surgery in a population of knee arthroplasty patients, using inertial sensors. When comparing preoperative measurements with postoperative measurements, patients walked faster had greater ROM, greater absolute value of minimal angle velocity, greater angle acceleration in stance phase, changed timing of gait-cycle-events and decreased variability. We consider all these changes to be indicative of improvement in gait, because patients walked faster. This interpretation could be strengthened by using patient reported outcome measures in combination with gait analysis and by comparing our results with gait measurements from healthy subjects. demonstrated that the greatest differences between the pre- and postoperative measurements were seen in the level-walking-at-comfortable-speed setting.

Interestingly Calliess et al. found few differences in gait at level-walking-at-comfortable-speed. The differences in spatiotemporal parameters and angular parameters after surgery, that the present study found, are consistent with findings from other studies [6, 18, 24]. Angular velocity and angular acceleration have only been reported in two other studies, to the authors knowledge [18, 29]. Jolles et al. [8] reported no difference in maximal angular velocity 3 months after surgery. As to acceleration, we also found a postoperative reduction of maximal acceleration during swing phase like Calliess et al. [6] but our finding was not significant. We identified a significant increase in maximal acceleration during stance-phase. Calliess et al. found a postoperative increase in the absolute value of Minimal acceleration in a start-to-run-test. They claimed that this measure of deceleration could act as a surrogate parameter for knee joint stability after joint replacement, but we did not find any significant difference in Minimal acceleration after surgery. The most likely explanation is that the forces of acceleration involved in starting to run and abruptly stopping are much greater than comfortable walking. It is therefore probable to find more significant differences in the setting presented by Calliess et al.

In our setting, variability decreased significantly after surgery. This finding is supported by Yakhdani et al. [7], who also found a significant postoperative reduction of variability of gait, measured as the standard deviation of the angular velocity in the first 10% of gait cycle time. The findings in this study and the findings by Yakhdani et al. suggests that postoperative reduction of variability is most likely a strategy adopted by patients, to cope for fear of instability (and not a sign of pathology) [7, 30]. Some patients may still feel pain or instability of the knee 4 months postoperatively. Stiffening of the joint by muscle-contraction could be a likely strategy to compensate for this. This is what the postoperative reduction of variability represents. Despite less pain and better function of the knee, 4 months after surgery, patients may still subconsciously choose to walk with a compensatory gait. It would therefore be interesting to investigate variability of gait in the same population, 1 year postoperatively, to see if this strategy is still present. This is currently underway.

Uphill gait and UKA vs. TKA.

Our findings showed that uphill walking reduced differences between pre- and postoperative measurements. At comfortable speed, uphill walking, patients still walked faster. But other parameters such as ROM, AUC, angular velocity, angular acceleration were not significantly different after surgery, as they were at level walking. Only at the self-determined maximal speed setting did we detect a significant difference in maximal acceleration. When we combined and averaged the pre- and postoperative results of UKA's with TKA's we did not see as many differences in gait, as in level walking. Uphill walking seems to not be as suitable as level walking, for detecting gait differences after knee arthroplasty. Wiik et al. demonstrated that downhill walking produced greater gait differences, before vs. after knee replacement, so based on our findings uphill walking could have a diminishing effect on detecting gait differences before vs. after knee replacement [25]. It would be interesting to investigate this setting with our method in the future. Interestingly, UKA's and TKA's had opposite developments in spatiotemporal parameters, ROM, AUC, minimal angle velocity, and maximal acceleration during stance-phase, when they walked uphill (**Appendix 1)**. UKA's and TKA's did not differ significantly in all of these parameters, but UKA's still had greater differences in these parameters than TKA's (when the postoperative measurements of UKA's and TKA's were compared with preoperative measurements). The reason then, for not finding more differences in gait at uphill walking, could be that we combined and averaged the gait-parameters of UKA's and TKA's. The greatest differences in gait between UKA's and TKA's were seen at the 7-degrees-inclination-maximal-speed setting. In this setting UKA's walked faster, had greater mobility, greater angle velocity in extension and greater acceleration in stance-phase. When examining the non-significant results, it also seems that improvements are generally greater for UKA’s (**Appendix 1)** and this improvement is most visible at uphill walking, at maximal speed. If a greater number of participants had been included, it might have been possible to find more significant changes.

Interestingly variability increased after surgery, when patients walked uphill (represented as an increase in the standard deviation of gait parameters). We assumed that decreased variability is a strategy for walking more carefully [7]. It seems then that patients seemed to walk more “relaxed” at uphill walking. The SD of Position of Minimal angle was less for UKA’s, meaning that extension occurred more regularly. It is important to note that decreased variability of timing of gait-cycle-events are not a sign of a stiffer joint, but a representation of more regular timing of steps. The SD of Minimal angle velocity were significantly greater for UKA’s, and if we accept our previous assumption about variability, the increase in SD of Minimal angle velocity is interpreted as the UKA’s walking with a less stiff joint than TKA’s. From **Appendix 1,** we can see that the variability parameters, which were significantly different when we compared all patients at level-walking-comfortable-speed, have also decreased after surgery at the uphill walking, maximal speed. Interestingly, when looking at these parameters, UKA’s had greater variability than TKA’s, though they were not significantly different. The differences in gait that we found between UKA’s and TKA’s in this setting, suggests that UKA’s have reached greater postoperative improvements in gait than TKA’s. The fact that UKA’s seems to have greater improvements in gait is supported by similar findings from other studies, which used VICON-technology [25, 31].

There were several limitations within our study. Magnetic interference could disturb measurements from the magnetometer. We made sure that no metallic objects were close to our sensors. The treadmill itself has been shown not be an issue, because our previous validation study demonstrated good reproducibility between measurements done on a treadmill and walking without a treadmill [23]. Some inaccuracy in connection with calibration of sensors exists, but our previous validation study demonstrated the sensors have excellent reproducibility [23]. A common limitation with studies using inertial sensors, are loose-skin-artefacts. We prevented this by using adhesive tape from Ioban (3M). This method of fastening the sensors to the skin, were also validated in our previous validation study [23]. Another limitation was the low number of participants. We used non-parametric tests in our statistical analysis, because we could not be certain that the measurements would all be normally distributed. Studies with a greater number of participants are needed to confirm the findings from our investigation and investigate whether the introduced parameters are normally distributed or not. In the future it would be desirable, when assessing the postoperative result of knee joint replacement, to combine gait analysis with patient reported outcome measures.

Conclusion

We found a clear postoperative improvement in gait four months after knee-replacement. These improvements were most obvious at level walking at comfortable speed. The parameters, which improved the most after knee joint replacement, were spatiotemporal parameters, gROM and area under the curve, Minimal angle velocity and Maximal acceleration in stance-phase. We found signs of decreased variability of gait after surgery, likely because patients adopt a stiffer gait after surgery. These parameters were SD of Maximal angle, SD of Maximal angle velocity, and SD of Maximal acceleration in swing-phase. We suggest that future gait studies include the before-mentioned parameters, because they are likely to be the most sensitive to gait changes after arthroplasty. Uphill walking seemed to diminish gait differences when we combined our two arthroplasty groups and compared them to the preoperative measurements. When we separated the two groups, uphill walking highlighted differences between the gait of UKA's and TKA's. UKA's had greater improvements in most categories of gait-parameters, but not all changes were significant. UKA's seemed to walk with greater variability than TKA's, possibly because they walked less stiff-legged than TKA's. This finding suggested that UKA's have recovered a different, possibly better gait, than TKA's. In the future we will continue to include subjects and see if our findings will persist. We will also investigate the 1-year-postoperative gait of subjects to see if their gait will continue to change. We recommend future investigations to combine gait-pattern analysis with patient-reported outcome-measures to see if any correlation between improvements of parameters and patient-reported improvement exist.

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Appendix 1

Level walking, at self-determined comfortable speed:

Parameter	Before (n = 14)	After (n=14)	After TKA (n=7)	After UKA (n=7)	Wilcoxon-test: p-value (before surgery vs. after surgery, n = 14).	Mann-Whitney U-test: p-value (UKA's vs. TKA's).
Step frequency	0.687	0.776	0.721	0.83	0.002	0.225
Step-period	1.459	1.335	1.441	1.228	0.022	0.225
Steps	80	90.786	84.285	97.285	0.002	0.224

Amplitude	37.457	45.479	42.387	48.571	0.048	0.277
SD of Amplitude	2.73	2.261	2.337	2.185	0.272	0.749
Minimal angle.	-1.629	-5.582	-4.671	-6.492	0.177	0.225
SD of Minimal angle.	1.882	2.056	2.017	2.095	0.397	1
Maximal angle.	35.826	39.895	37.712	42.077	0.47	0.406
SD of Maximal angle.	1.927	1.310	1.444	1.175	0.022	0.225
Position of Minimal angle.	2.752	2.079	2.531	1.627	0.056	0.338
SD of Position of Minimal angle.	0.532	0.107	0.137	0.077	0.003	0.017
Position of Maximal angle.	-0.0171	-0.021	-0.015	-0.027	0.552	0.141
SD of Position of Maximal angle.	0.104	0.105	0.1	0.11	0.916	0.521
Minimal angle velocity.	-34.697	-41.489	-37.078	-45.898	0.074	0.225
SD of Minimal angle velocity.	6.79	7.328	6.214	8.441	0.51	0.225
Maximal angle velocity.	41.865	42.537	42.897	42.177	0.683	0.277
SD of Maximal angle velocity.	8.109	5.567	5.107	6.027	0.011	0.482
Position of Minimal angle velocity.	0.705	0.940	0.888	0.991	0.041	0.482
SD of Position of minimal angle velocity.	0.655	0.549	0.767	0.33	0.432	0.337
Position of Maximal angle velocity.	5.717	5.696	5.684	5.708	0.593	0.848
SD of Position of maximal angle velocity.	0.107	0.120	0.151	0.088	0.9	0.138
Maximal acceleration during swing-phase.	74.047	66.510	68.001	65.018	0.551	0.949
SD of Maximal acceleration during swing-phase.	40.562	25.401	24.79	26.012	0.056	0.949
Minimal acceleration during swing-phase.	-111.337	-110.716	-116.061	-105.37	0.397	0.565
SD of Minimal acceleration during swing-phase.	44.955	40.410	38.27	42.55	0.51	0.949
Maximal acceleration during stance-phase	68.396	104.958	89.865	120.05	0.03	0.277
SD of Maximal acceleration during stance-phase.	32.855	36.999	29.7	44.297	0.363	0.064
Position of Maximal acceleration during swing-phase.	5.414	5.327	5.227	5.427	0.48	0.443
SD of Position of Maximal acceleration during swing-phase.	0.243	0.285	0.267	0.302	0.329	0.898
Position of Minimal acceleration during swing-phase.	-0.148	-0.173	-0.122	-0.222	0.345	0.158
SD of Position of Minimal acceleration during swing-phase.	0.344	0.394	0.385	0.402	0.346	0.949
The Position of Maximal acceleration during stance-phase.	1.106	1.289	1.098	1.478	0.052	0.085

SD of Position of Maximal acceleration during stance-phase	0.439	0.234	0.247	0.22	0.071	0.654
AUC	78.455	109.361	95.461	123.26	0.008	0.11
SD of AUC.	9.518	11.417	11.331	11.502	0.158	0.655
Walking Speed.	2.228	3.029	2.585	3.471	0.008	0.124

Level walking, at self-determined maximal speed.

Parameter	Before (n = 14)	After (n=14)	After TKA (n=7)	After UKA (n=7)	Wilcoxon-test: p-value (before surgery vs. after surgery, n = 14).	Mann-Whitney U-test: p-value (UKA's vs. TKA's).
Step frequency	0.829	0.886	0.811	0.960	0.024	0.047
Step-period	1.216	1.136	1.277	0.994	0.167	0.047
Steps	47.214	51.071	46.286	55.857	0.014	0.025
Amplitude	40.774	48.333	43.667	52.999	0.363	0.338
SD of Amplitude	2.331	2.649	2.687	2.610	0.331	0.848
Minimal angle.	-3.274	-7.899	-5.843	-9.954	0.221	0.565
SD of Minimal angle.	1.621	2.006	1.766	2.246	0.245	0.338
Maximal angle.	37.501	40.433	37.823	43.043	0.925	0.949
SD of Maximal angle.	1.704	1.606	1.601	1.610	0.875	0.749
Position of Minimal angle.	2.891	2.113	2.499	1.727	0.149	0.406
SD of Position of Minimal angle.	0.823	0.111	0.137	0.084	0.077	0.521
Position of Maximal angle.	-0.021	-0.024	-0.029	-0.020	0.754	0.651
SD of Position of Maximal angle.	1.269	0.534	0.971	0.097	0.656	0.847
Minimal angle velocity.	-37.386	-42.349	-37.573	-47.126	0.510	0.620
SD of Minimal angle velocity.	7.275	7.526	5.469	9.584	0.638	0.085
Maximal angle velocity.	43.994	42.701	43.744	41.659	0.397	0.048
SD of Maximal angle velocity.	7.830	6.491	6.780	6.201	0.683	0.338
Position of Minimal angle velocity.	0.717	1.126	1.249	1.003	0.002	0.749
SD of Position of minimal angle velocity.	0.312	0.509	0.579	0.439	0.272	0.949
Position of Maximal angle velocity.	5.350	5.643	5.609	5.677	0.593	0.701
SD of Position of maximal angle velocity.	0.448	0.510	0.136	0.884	0.666	0.199
Maximal acceleration during swing-phase.	84.873	69.219	74.323	64.114	0.109	0.110
SD of Maximal acceleration during swing-phase.	38.819	33.819	36.187	31.450	0.778	0.180
Minimal acceleration during swing-phase.	-110.799	-103.910	-109.230	-98.590	0.245	0.110
SD of Minimal acceleration during swing-phase.	46.611	41.626	44.247	39.004	0.433	0.482

Maximal acceleration during stance-phase	86.361	106.449	91.241	121.657	0.470	0.338
SD of Maximal acceleration during stance-phase.	42.885	38.102	34.313	41.891	0.826	0.565
Position of Maximal acceleration during swing-phase.	5.271	5.259	5.193	5.324	0.593	0.949
SD of Position of Maximal acceleration during swing-phase.	0.208	0.236	0.220	0.253	0.208	0.140
Position of Minimal acceleration during swing-phase.	-0.084	-0.179	-0.241	-0.116	0.177	0.224
SD of Position of Minimal acceleration during swing-phase.	0.769	0.639	0.420	0.857	0.330	0.482
The Position of Maximal acceleration during stance-phase.	1.236	1.415	1.201	1.629	0.022	0.013
SD of Position of Maximal acceleration during stance-phase	0.325	0.489	0.740	0.237	0.433	0.949
AUC	90.531	124.151	104.239	144.063	0.064	0.180
SD of AUC.	9.680	11.356	10.477	12.234	0.470	0.338
Walking Speed.	3.557	4.414	3.686	5.143	0.003	0.030

7 degree inclination, at self-determined comfortable speed.

Parameter	Before (n = 14)	After (n=14)	After TKA (n=7)	After UKA (n=7)	Wilcoxon-test: p-value (before surgery vs. after surgery, n = 14).	Mann-Whitney U-test: p-value (UKA's vs. TKA's).
Step frequency	0.728	0.834	0.784	0.884	0.001	0.179
Step-period	1.379	1.189	1.303	1.074	0.011	0.179
Steps	82.714	96.357	90.429	102.286	0.001	0.200
Amplitude	37.023	42.416	40.157	44.674	0.198	0.338
SD of Amplitude	2.199	2.926	2.814	3.037	0.124	0.565
Minimal angle.	-1.715	-2.934	-2.737	-3.130	0.778	0.848
SD of Minimal angle.	1.472	2.249	2.193	2.306	0.048	0.609
Maximal angle.	35.308	39.481	37.420	41.543	0.245	0.482
SD of Maximal angle.	1.636	1.991	1.957	2.024	0.074	0.277
Position of Minimal angle.	3.441	2.994	3.604	2.383	0.198	0.064
SD of Position of Minimal angle.	0.360	0.459	0.800	0.119	0.490	0.015
Position of Maximal angle.	-0.017	-0.032	-0.036	-0.029	0.123	0.362
SD of Position of Maximal angle.	0.541	0.544	0.969	0.120	0.260	0.898
Minimal angle velocity.	-31.747	-36.172	-32.153	-40.191	0.272	0.180
SD of Minimal angle velocity.	5.798	8.150	7.800	8.500	0.074	0.655

Maximal angle velocity.	39.543	39.786	39.709	39.863	0.470	0.565
SD of Maximal angle velocity.	6.326	6.446	5.476	7.416	0.826	0.064
Position of Minimal angle velocity.	0.611	0.844	0.751	0.936	0.009	0.096
SD of Position of minimal angle velocity.	0.602	0.323	0.297	0.349	0.975	0.306
Position of Maximal angle velocity.	5.639	5.631	5.589	5.673	0.450	1.000
SD of Position of maximal angle velocity.	0.121	0.147	0.166	0.129	0.194	0.247
Maximal acceleration during swing-phase.	65.149	59.586	59.589	59.584	0.331	0.949
SD of Maximal acceleration during swing-phase.	30.405	29.186	23.053	35.319	0.875	0.110
Minimal acceleration during swing-phase.	-103.228	-96.719	-99.469	-93.969	0.470	0.338
SD of Minimal acceleration during swing-phase.	43.996	43.617	44.393	42.841	0.975	0.406
Maximal acceleration during stance-phase	69.680	86.329	69.529	103.130	0.198	0.110
SD of Maximal acceleration during stance-phase.	33.928	39.947	36.990	42.904	0.397	0.338
Position of Maximal acceleration during swing-phase.	5.334	5.224	5.071	5.377	0.294	0.179
SD of Position of Maximal acceleration during swing-phase.	0.293	0.384	0.390	0.379	0.198	0.898
Position of Minimal acceleration during swing-phase.	-0.155	-0.222	-0.211	-0.233	0.245	0.564
SD of Position of Minimal acceleration during swing-phase.	0.345	1.139	1.296	0.983	0.026	0.222
The Position of Maximal acceleration during stance-phase.	1.091	1.409	1.287	1.530	0.003	0.085
SD of Position of Maximal acceleration during stance-phase	0.754	0.476	0.629	0.324	0.826	0.848
AUC	84.209	101.944	92.044	111.844	0.109	0.180
SD of AUC.	8.885	12.744	12.363	13.124	0.331	0.406
Walking Speed.	2.593	3.443	2.886	4.000	0.003	0.034

7 degree inclination: walking at self-determined maximal speed.

Parameter	Before (n = 14)	After (n=14)	After TKA (n=7)	After UKA (n=7)	Wilcoxon-test: p-value (before surgery vs. after surgery, n = 14).	Mann-Whitney U-test: p-value (UKA's vs. TKA's).
Step frequency	0.853	0.885	0.821	0.949	0.286	0.048
Step-period	1.176	1.117	1.234	1.000	0.451	0.048
Steps	48.357	50.429	46.571	54.286	0.310	0.040

Amplitude	39.121	42.385	38.953	45.817	0.331	0.338
SD of Amplitude	2.553	2.364	2.399	2.329	0.975	0.949
Minimal angle.	-3.061	-3.094	-1.980	-4.209	0.826	0.225
SD of Minimal angle.	1.799	1.835	1.734	1.936	0.594	0.565
Maximal angle.	36.061	39.294	36.976	41.611	0.331	0.482
SD of Maximal angle.	1.665	1.494	1.473	1.516	0.638	0.655
Position of Minimal angle.	3.077	2.424	2.844	2.003	0.198	0.655
SD of Position of Minimal angle.	0.259	0.464	0.839	0.089	0.975	0.047
Position of Maximal angle.	-0.031	-0.033	-0.026	-0.040	0.833	0.363
SD of Position of Maximal angle.	0.531	0.532	0.961	0.103	0.801	0.949
Minimal angle velocity.	-33.959	-36.621	-31.804	-41.439	0.433	0.064
SD of Minimal angle velocity.	7.179	5.709	4.534	6.883	0.177	0.025
Maximal angle velocity.	42.268	39.527	39.331	39.723	0.221	0.655
SD of Maximal angle velocity.	7.790	5.144	5.133	5.156	0.124	0.848
Position of Minimal angle velocity.	0.670	0.919	0.830	1.007	0.013	0.179
SD of Position of minimal angle velocity.	0.496	0.329	0.276	0.381	0.778	0.224
Position of Maximal angle velocity.	5.634	5.607	5.544	5.670	0.379	0.701
SD of Position of maximal angle velocity.	0.532	0.541	0.181	0.900	0.972	0.479
Maximal acceleration during swing-phase.	76.071	59.786	59.054	60.517	0.056	0.848
SD of Maximal acceleration during swing-phase.	42.203	28.211	25.143	31.280	0.140	0.338
Minimal acceleration during swing-phase.	-100.797	-96.231	-94.643	-97.819	0.683	0.406
SD of Minimal acceleration during swing-phase.	44.706	36.654	35.663	37.646	0.124	0.225
Maximal acceleration during stance-phase	74.606	89.689	72.003	107.374	0.158	0.085
SD of Maximal acceleration during stance-phase.	36.727	33.081	25.914	40.249	0.730	0.110
Position of Maximal acceleration during swing-phase.	5.306	5.196	5.040	5.353	0.660	0.159
SD of Position of Maximal acceleration during swing-phase.	0.322	0.342	0.360	0.324	0.660	0.848
Position of Minimal acceleration during swing-phase.	-0.176	-0.256	-0.293	-0.219	0.624	0.701
SD of Position of Minimal acceleration during swing-phase.	1.096	1.354	1.186	1.523	0.683	0.701
The Position of Maximal acceleration during stance-phase.	1.179	1.439	1.331	1.546	0.011	0.073
SD of Position of Maximal acceleration during stance-phase	0.279	0.376	0.489	0.263	0.650	0.949

AUC	88.604	102.976	87.003	118.949	0.198	0.085
SD of AUC.	9.394	10.290	10.391	10.189	0.433	0.655
Walking Speed.	3.700	4.221	3.600	4.843	0.115	0.047

Appendix 2