Hip and knee kinematics of the forward lunge one year after unicondylar and total knee arthroplasty

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ABSTRACT

Patients with unicondylar knee arthroplasty (UKA) report higher functionality compared to those with total knee arthroplasty (TKA). However, these patients should also be assessed during more demanding tasks in order to appreciate their true functionality. The forward lunge (FL) is a motor task commonly used in clinics to evaluate functional recovery after knee replacement surgery. Unfortunately, clear evidence comparing FL kinematics between patients with UKA and TKA is still missing. The purpose of this study was to compare hip and knee joint kinematics during the FL between patients with UKA, TKA and controls. Twenty subjects (8 TKA, 6 UKA, 6 controls) underwent 3D motion analysis during a FL. Differences in hip and knee kinematics between groups were identified using statistical parametric mapping. We concluded that patients with TKA demonstrated reduced knee and hip flexion angles during the loaded phase of the FL, which could have been an attempt to unload the knee joint. This is in contrast to patients with UKA, who showed similar knee and hip joint kinematics compared to controls throughout the entire FL. It seems that retaining the cruciate ligaments is beneficial for the execution of a complex motor task such as the FL.

1. Introduction

Knee replacement is frequently used as a treatment option for the management of end-stage knee osteoarthritis [Lostak et al., 2016], which is mainly characterized by pain, stiffness and knee joint swelling. A knee replacement aims to restore normal knee function and to enhance quality of life [Baert et al., 2016]. Total knee arthroplasty (TKA) is the most commonly performed knee replacement procedure [Engh et al., 2014, Bolink et al., 2015]. It replaces all articular surfaces of the knee joint with metal alloys and synthetic components. Nevertheless, up to 30% of knee replacement candidates demonstrate osteoarthritis that is limited to only one knee joint compartment, most commonly the medial tibiofemoral compartment [Longo et al., 2015]. As a result, the replacement of the entire knee joint, as performed in TKA, might not be necessary in these patients [Arirachakaran et al., 2015]. Unlike TKA, unicondylar knee arthroplasty (UKA) replaces either the lateral or medial tibiofemoral compartment. This has been associated with several advantages, such as femoral and tibial bone stock sparing, reduced

blood loss, reduced risk of infection and a shorter period of hospital stay [Leffler et al., 2012, Longo et al., 2015]. Moreover, a UKA procedure preserves the cruciate ligaments, which are sacrificed during a TKA procedure. As the cruciate ligaments provide essential somatosensory (e.g. proprioception) information from the knee [Wodowski et al., 2016], one may assume that retaining the cruciate ligaments is beneficial for recovering normal knee joint biomechanics during walking or other daily movements [Leffler et al., 2012]. Given these benefits, surgeons increasingly opt for a UKA implant, especially in patients with unilateral knee joint degeneration and intact cruciate ligaments [Orthopride, 2014].

In Western countries, a drastic increase in number of knee arthroplasty procedures is to be expected by 2030 [Pabinger et al., 2015]. This increase will be due, among other reasons, to the increasing amount of mostly younger patients in need of a knee replacement [Pabinger et al., 2015]. These younger patients are known to have higher postoperative expectations regarding the recovery of a normal knee function [Bonnefoy-Mazure et al., 2016]. Motion analysis has

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Table 1
Subjects' characteristics.

	UKA (n = 6) Mean ± SD	TKA (n = 8) Mean ± SD	Controls (n = 6) Mean ± SD	Significance
Gender	M = 4, F = 2	M = 2, F = 6	M = 5, F = 1	A: NS; B: NS; C: NS
Age (years)	66.50 ± 9.71	64.50 ± 3.85	63.33 ± 3.61	A: NS; B: NS; C: NS
Weight (kg)	86.50 ± 18.85	89.00 ± 17.74	73.80 ± 5.88	A: NS; B: NS; C: NS
Height (m)	1.69 ± 0.14	1.65 ± 0.06	1.68 ± 0.06	A: NS; B: NS; C: NS
BMI (kg/m^2)	30.08 ± 4.33	32.99 ± 7.14	26.03 ± 1.55	A: NS; B: NS; **C: 0.03**

UKA = unicondylar knee arthroplasty; TKA = total knee arthroplasty; BMI = body mass index; SD = standard deviation; NS: non-significant; Statistical significance was set at $p < 0.05$; Bold values indicate a significant difference between groups; A: significant difference between UKA and TKA; B: significant difference between UKA and controls; C: significant difference between TKA and controls.

already been used to assess in vivo knee function during daily tasks (e.g. gait) in these patients. Yet, it appears that gait is not a sufficiently challenging task for these patients, and does not fully reflect functional recovery [Komnik et al., 2015]. Therefore, as suggested in a recent review, patients with UKA and TKA should be assessed during more demanding tasks, in order to identify potential kinematical abnormalities that do not occur during gait [Komnik et al., 2015].

The forward lunge (FL) is a functional task that can be used to assess the functional outcome after knee arthroplasty [Engh et al., 2014]. In this study, authors reported that patients with TKA need less time to complete a lunge task two years after surgery compared to their pre-operative baseline. Moreover, patients were able to perform the FL with similar peak knee flexion values at the operated leg compared to the non-operated leg [Engh et al., 2014]. Hence, it was also reported that patients executed a FL with less knee flexion compared to controls, even 1.5 years post-surgery. These findings are in agreement with a study which showed that patients with TKA only use about 70% of their available passive knee flexion range of motion, indicating that deep flexion was avoided during FL [McClelland et al., 2017]. Previous studies only compared TKA patients with controls, and did not include any patients with UKA. This is remarkable given that UKA preserves the cruciate ligaments, which are known to provide essential somatosensory (e.g. proprioception) information arising from the knee [Wodowski et al., 2016]. One may then conclude that retaining the cruciates is highly beneficial for the execution of complex motor tasks, such as a FL [Leffler et al., 2012; Alkjaer et al., 2009]. Moreover, it has been demonstrated that the mechanical contribution of the cruciate ligaments is crucial during the performance of a FL [Alkjaer et al., 2009].

Studies in non-TKA populations, such as in patients with ACL or meniscal injury, included the hip or ankle in the motion analysis, providing both clinicians and researchers with a better understanding of the occurring compensation strategies used either to unload the knee or to maintain equilibrium [Mattacola et al., 2004]. To the best of our knowledge, such kinematical analyses of the knee and hip joint during a FL still needs to be conducted in the UKA and TKA populations. Another concern regarding the available literature might be that only peak knee joint angles were reported in order to assess function and performance of a FL. Yet, a motion analysis produces kinematical curves, which yields valuable information regarding the underlying movement quality and motor control [Mattacola et al., 2004]. This shortcoming has been tackled in the present study by implementing statistical parametric mapping (SPM) [Pataky et al., 2015]. This tool enables the identification of significant differences between kinematical curves, by first computing the magnitude of the difference between curves at each time node, and second, by calculating critical thresholds at which only 5% ($\alpha = 0.05$) of similarly smooth curves would be expected to traverse.

Therefore, the main aim of this study was to compare sagittal hip and knee joint kinematics of a FL between patients with UKA, TKA and controls. We hypothesized that controls and patients with UKA would demonstrate a better execution of the FL compared to patients with TKA. More specifically, a SPM analysis was used to compare kinematical curves of the hip and knee joint between groups.

2. Methods

2.1. Subjects

Knee arthroplasty patients were recruited among the patients of one experienced knee surgeon and were assessed for eligibility to participate in this study. Fourteen subjects who had undergone knee arthroplasty surgery (6 medial UKA and 8 posterior stabilized TKA) were included in this study. Patients were recruited if they had undergone a knee replacement 12 months but no longer than 14 months prior to their inclusion. Subjects were excluded if they had any comorbidity that might affect the performance of a FL such as previous trauma to the lower limbs, other orthopedic conditions, a neurologic or systemic disease. Six control subjects, within a similar age range, were recruited to participate in this study. A written informed consent was obtained from all participants prior to initiation of the study, all test procedures were in accordance with the ethical standards of the local institutional research committee and with the Helsinki declaration [World Medical, 2013]. Subject characteristics are presented in Table 1.

2.2. Patient reported outcome measures (PROMs)

All subjects filled out the Oxford Knee Score (OKS) [Dawson et al., 1998], which specifically evaluates knee functionality in knee arthroplasty patients. The Tampa Scale for Kinesiophobia (TSK) was used to assess movement related fear and fear for (re)-injury among participants [Miller et al., 1991].

2.3. Clinical examination

One well-experienced physiotherapist carried out the clinical examination of all participants. Sagittal range of motion (ROM) measurements of the knee joint were performed using a standard goniometer [Brosseau et al., 2001]. Strength of the lower limb muscles was evaluated by means of a break test, using a hand-held dynamometer (MicroFET2, Hoggan Health Industries, Salt Lake City, US) [Lu et al., 2011]. Mean strength values (based on three trials) were calculated for the gluteus medius, quadriceps, hamstrings and gluteus maximus, respectively (Fig. 1).

2.4. Motion capture, spatiotemporal and kinematic analysis

Subjects were instructed to take a large, comfortable and safe step forward (without losing equilibrium) and to bend through the knee as far as possible without losing heel contact while keeping the trunk upright. This functional movement was recorded with a six camera-based 3D Optitrack Flex 13 motion capture system (NaturalPoint Inc, Optitrack, Corvallis, US). Reflective markers were placed according to the Liverpool John Moores University (LJMU) Lower Limb and Trunk model [Vanrenterghem et al., 2010]. Motion capture data were collected at a sampling rate of 120 frames/second. Motion capture data processing was performed in Visual 3D V5 software (C-motion Inc,

Fig. 1. Subject position and placement of the dynamometer for respectively hip abduction, knee extension, knee flexion and hip extension.

Germantown, US), filtering was applied using a Butterworth filter with a cut-off frequency set at 6 Hz. Knee and hip joint axis were computed using a functional joint calibration procedure [De Rosario et al., 2017].

A temporal analysis of the FL was performed by identifying marker trajectory-based events and subsequent phases. This methodological approach enables an outside-laboratory assessment of the forward lunge, and could easily be implemented in clinical practice. The following events were used in the analysis of the FL: movement initiation (MI), initial contact (IC), maximal knee flexion (MKF), heel off (HO) and foot flat (FF). Marker trajectory-based identifications of all events are presented in Fig. 2. Following phases of the FL were used for the temporal analysis of the FL: forward swing phase (FSP) from movement initiation to initial contact, loading phase (LP) from initial contact to maximal knee flexion, push back phase (PBP) from maximal knee flexion to heel off and step back phase (SBP) from heel off to foot flat. Fig. 3 shows an overview of the occurring events and phases.

2.5. Statistics

A Kruskal-Wallis followed by a post-hoc Dunn's test was performed to identify statistically significant differences between groups for age, weight, height, BMI, ROM, muscle strength, PROMs and phase duration of the forward lunge. All statistical tests were conducted in SPSS Statistics 20 (IBM, USA). Statistical parametric mapping (SPM) [Friston et al., 2007] was used to assess statistically significant differences between groups for gait kinematics. This statistical tool enables an indepth analysis of time-series data, as obtained during a biomechanical motion analysis [Pataky et al., 2015]. Moreover, similarly to conventional statistics, SPM is a hypothesis testing tool, which allows the identification of significant differences between groups. This is in contrast to other statistical tests such as principle components analysis (PCA) or functional data analysis (FDA), which are mostly used for biomechanical data exploration. In this study a one-way between-subjects ANOVA test followed by a Bonferroni correction for multiple testing was used to compare the resulting sagittal kinematics of the hip and knee joint between groups. The scalar output SPM {t} was calculated for each time node separately and in order to test the null hypothesis, a critical threshold was calculated at which only $\alpha = 0.05$ of smooth random curves would be expected to traverse. This threshold was based upon estimates of trajectory smoothness via temporal gradients [Friston et al., 2007], and Random Field Theory expectations regarding the field wide maximum [Adler, 2007]. Adjacent points exceeding this threshold are called "supra-threshold clusters" for which specific p-values were calculated using Random Field Theory, indicating the probability with which the supra-threshold clusters would be produced by a random field process with the same temporal smoothness. Conceptually, a SPM analysis is similar to the calculation and interpretation of a conventional statistical test (e.g. *t*-test or ANOVA); if the SPM scalar output crosses the critical threshold at any time node, the null hypothesis is rejected. All SPM analyses were

implemented using open-source spm1d code (v4.M.0.4, www.spm1d.org) in Matlab (R2016b, 8.6.0, Matworks Inc, Natick, MA).

3. Results

3.1. Patient reported outcome measures

No significant differences in PROMs were observed between knee replacement groups. A mean OKS-score of 44.00 (± 2.76) and 41.50 (± 6.19) was found for UKA and TKA subjects, respectively. A mean TSK score of 35.00 (± 14.14) and 36.00 (± 7.42) was found for patients with a UKA and TKA, respectively. This was lower than the clinical threshold of 37, showing that patients were, on average, not subject to kinesiophobia [Miller et al., 1991].

3.2. Clinical examination

The results of the clinical examination are presented in Table 2. When comparing UKA and TKA groups, no significant differences were found regarding knee ROM or muscle strength of the glutei, hamstrings and quadriceps. However, both patients groups (UKA and TKA) did show significantly less knee flexion ROM at their arthroplasty side compared to controls (p = 0.04). Strength measurements revealed significant differences for each muscle group that was included in the examination. UKA and TKA groups showed significantly less gluteus medius strength compared to the control group both at the non-operated and arthroplasty side. Significantly lower gluteus maximus strength was also found in patients with a TKA compared to the controls (p = 0.01). Hamstrings strength was significantly lower in the TKA group compared to the control group at the arthroplasty and non-operated side (p = 0.01). Last, significantly lower quadriceps strength was found at the arthroplasty side of patients with TKA compared to controls (p = 0.01).

3.3. Temporal analysis

The resulting FL temporal parameters for all groups are presented in Table 3. Patients in the arthroplasty groups completed the lunge with their arthroplasty side. No significant differences in phase duration were demonstrated between groups. Also the time to complete task did not differ significantly across groups.

3.4. Kinematic analysis

Sagittal kinematics of the hip and knee during the FL, along with the according SPM scalar output, are shown in Fig. 4. Patients with TKA demonstrated significantly less hip flexion than controls between 35% and 55% of the lunge movement (Fig. 4A and B). No significant differences were found between UKA and controls regarding sagittal hip joint kinematics. Patients with TKA also demonstrated significantly less

2a Event timing: movement initiation
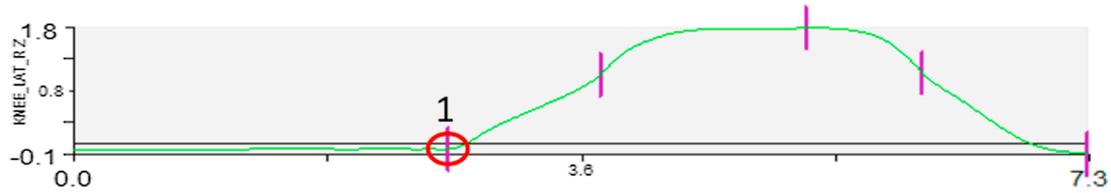
Graph representing the displacement of the right lateral knee marker along the Z-axis (anterior/posterior direction); 1 = movement initiation = when the lateral knee marker of the moving leg starts to move in the anterior direction

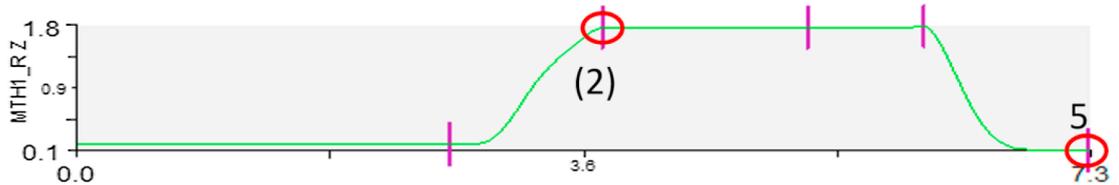**2b Event timing: initial contact and heel off**
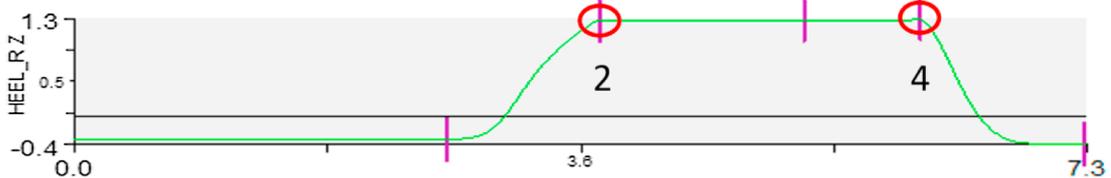
Graph representing the displacement of the right heel marker along the Z-axis (anterior/posterior direction); 2 = initial contact in case of a rear foot strike = abrupt stop in the anterior displacement of the heel marker; 4 = heel off = when the heel marker of the moving leg starts to move in the posterior direction

2c Event timing: maximal knee flexion
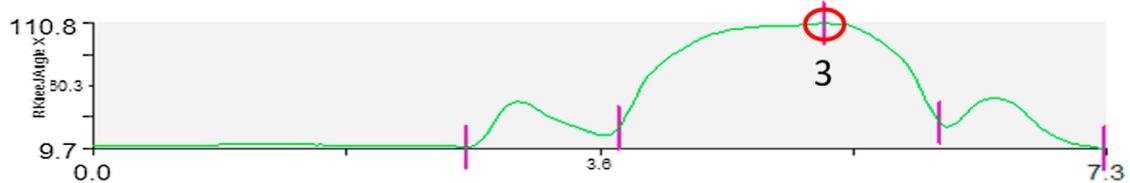
Graph showing sagittal knee angle (flexion/extension); 3 = maximal sagittal knee flexion angle = time point at which maximal knee flexion is reached, between initial contact and heel off events

2d Event timing: initial contact and foot flat

Graph representing the displacement of the right metatarsal head 1 marker along the Z-axis (anterior/posterior direction); (2) = initial contact in case of a forefoot strike = abrupt stop in the anterior displacement of the marker on metatarsal head one; 5 = foot flat = when the marker on metatarsal head one stopped moving in the posterior or downward direction

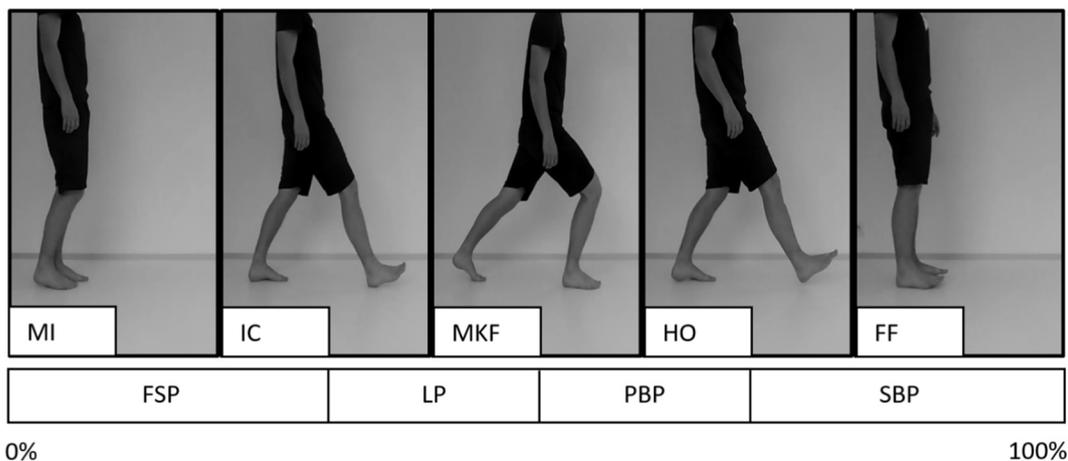**Fig. 2.** Event timing of the forward lunge based marker trajectories and kinematics.

Fig. 3. Overview of events and phases of the forward lunge. MI: Movement Initiation; IC: Initial Contact; MKF: Maximal Knee Flexion; HO: Heel Off; FF: Foot Flat; FSP: Forward Swing Phase; LP: Loading Phase; PBP: Push Back Phase; SBP: Step Back Phase.

Table 2
Clinical examination.

	UKA (n = 6) Mean ± SD	TKA (n = 8) Mean ± SD	Controls (n = 6) Mean ± SD	Significance
ROM				
– Knee extension (°)	2.83 ± 2.79	0.50 ± 1.41	0.00 ± 0.00	A: NS; B: NS; C: NS
– Knee flexion (°)	122.67 ± 5.24	127.13 ± 7.92	140.67 ± 5.65	A: NS; **B: 0.01**; **C: 0.04**
Strength				
– Gluteus medius (N)	151.65 ± 37.58	153.65 ± 27.94	272.56 ± 32.14	A: NS; **B: 0.01**; **C: 0.01**
– Gluteus maximus (N)	134.61 ± 35.67	123.41 ± 32.17	185.46 ± 44.54	A: NS; B: NS; **C: 0.03**
– Hamstrings (N)	103.91 ± 29.65	84.60 ± 25.07	180.04 ± 22.01	A: NS; B: NS; **C: 0.00**
– Quadriceps (N)	204.53 ± 67.06	162.51 ± 38.24	268.62 ± 41.49	A: NS; B: NS; **C: 0.01**
– Ham/Q ratio	0.60 ± 0.33	0.52 ± 0.13	0.68 ± 0.12	A: NS; B: NS; C: NS

UKA = unicondylar knee arthroplasty; TKA = total knee arthroplasty; ROM = range of motion; SD = standard deviation; NS = non-significant, Statistical significance was set at $p < 0.05$; Bold values indicate a significant difference between groups; A: significant difference between UKA and TKA; B: significant difference between UKA and controls; C: significant difference between TKA and controls.

knee flexion compared to control subjects, between 35% and 50% of the forward lunge (Fig. 4C and D). Similarly to the hip kinematics, no significant differences were observed between UKA and controls.

4. Discussion

The main finding of the current pilot study was that patients with TKA performed the forward lunge with significantly less hip and knee flexion compared to patients with UKA and controls, one year after knee replacement surgery. More specifically, patients with TKA demonstrated reduced hip and knee flexion angles at the end of the loading phase and at the beginning of the push back phase of the FL. These phases are highly demanding parts of the FL, since they require an optimal neuromuscular control in order to maintain equilibrium and to change movement direction [Comfort et al., 2015]. Patients with a UKA did not show significant differences in hip and knee joint kinematics during the different phases of the FL compared to controls.

The FL has been reported as a challenging task for knee (replacement) patients, as it targets the entire biomechanical chain and requires optimal motor control to perform the movement adequately [Alkjær et al., 2009]. However, only few studies have assessed the underlying kinematics or temporal features associated with the execution of this functional movement in knee replacement patients and no studies evaluated possible kinematical differences in patients with TKA and UKA. Engh et al. reported that patients with knee arthroplasty needed significantly less time to perform the FL at 2 years follow-up compared to preoperative measurements. The authors mentioned more symmetrical movement patterns (maximal knee flexion) between both legs, but did not report any kinematic data. A recent study demonstrated that TKA patients, unlike controls, did not use their available active ROM to perform activities such as the FL [McClelland et al., 2017]. These findings are in agreement with results reported in this study, since patients with TKA demonstrated less knee flexion than controls during the FL. No difference was observed regarding active knee flexion range of motion between patient with a knee replacement. Yet, it seems that patients with UKA reached higher knee flexion angles during a FL than those with TKA. This might imply that the available range of motion at

the knee is not necessarily the most important factor when performing a FL. Perhaps, knee joint stability and the presence of the cruciate ligaments could be of greater importance when performing weight bearing activities [Levinger et al., 2012]. Especially since these ligaments are known to contribute to knee joint mechanics, proprioception and accurate limb positioning in space [Fridén et al., 2001]. Moreover, it has been demonstrated in computational models and in vivo studies that the cruciate ligaments have a tremendous mechanical contribution when performing a forward lunge [Alkjaer et al., 2009]. It could also very-well be that patients with posterior stabilised TKA did not reach a degree of flexion that is similar to those with UKA due to the mechanical features that are inherent to the implant design and surgical procedure [Matsumoto et al., 2012]. Nonetheless, findings from this study suggested that the cruciate ligaments have a major role in the performance of the FL in patients with knee replacement. No significant difference was demonstrated between the UKA and TKA groups with respect to knee flexion angles during the FL. Perhaps due to the small sample size, the statistical analysis might have failed to demonstrate a significant difference. Yet, these findings are in agreement with McClelland et al. who reported that patients with TKA did not use their full knee ROM (68.3%) when performing functional activities such as the FL [McClelland et al., 2017].

We demonstrated a reduced hip flexion angle during FL in patients with TKA. Whereas no other studies have investigated both hip and knee kinematics in patients with a knee replacement, this compensation mechanism has been observed in other populations such as in patients with ACL or meniscal injury [Hall et al., 2015, Riemann et al., 2002]. In this study, the reduced hip flexion angle was achieved by leaning backwards with the trunk, which resulted in a posterior shift of the centre of mass. This strategy is known to unload the knee joint of the leading leg [Riemann et al., 2002, Hofmann et al., 2017]. However, kinetics are needed to further evaluate this hypothesis.

Previous studies emphasized the role of hip and knee extensor strength during the lunge task [Comfort et al., 2015, Riemann et al., 2002]. Riemann et al. reported that the FL predominantly requires a concentric activity of the hip extensor muscles, whereas knee extensors mainly have an eccentric role [Riemann et al., 2002]. The significantly

Table 3
Temporal parameters of the forward lunge sub-phases.

	UKA (n = 6) Mean ± SD	TKA (n = 8) Mean ± SD	Controls (n = 6) Mean ± SD	Significance
Forward swing phase (%)	17.69 ± 2.06	14.24 ± 3.18	20.07 ± 5.62	NS
Loading phase (%)	27.91 ± 10.08	24.99 ± 18.39	32.13 ± 14.68	NS
Push back phase (%)	39.09 ± 9.70	42.96 ± 14.76	28.19 ± 15.05	NS
Step back phase (%)	15.31 ± 4.49	17.81 ± 8.24	19.61 ± 6.81	NS
Time to Complete Task (s)	5.73 ± 0.73	6.02 ± 0.80	4.97 ± 1.31	NS

UKA = unicondylar knee arthroplasty; TKA = total knee arthroplasty; SD = standard deviation; NS = non-significant.
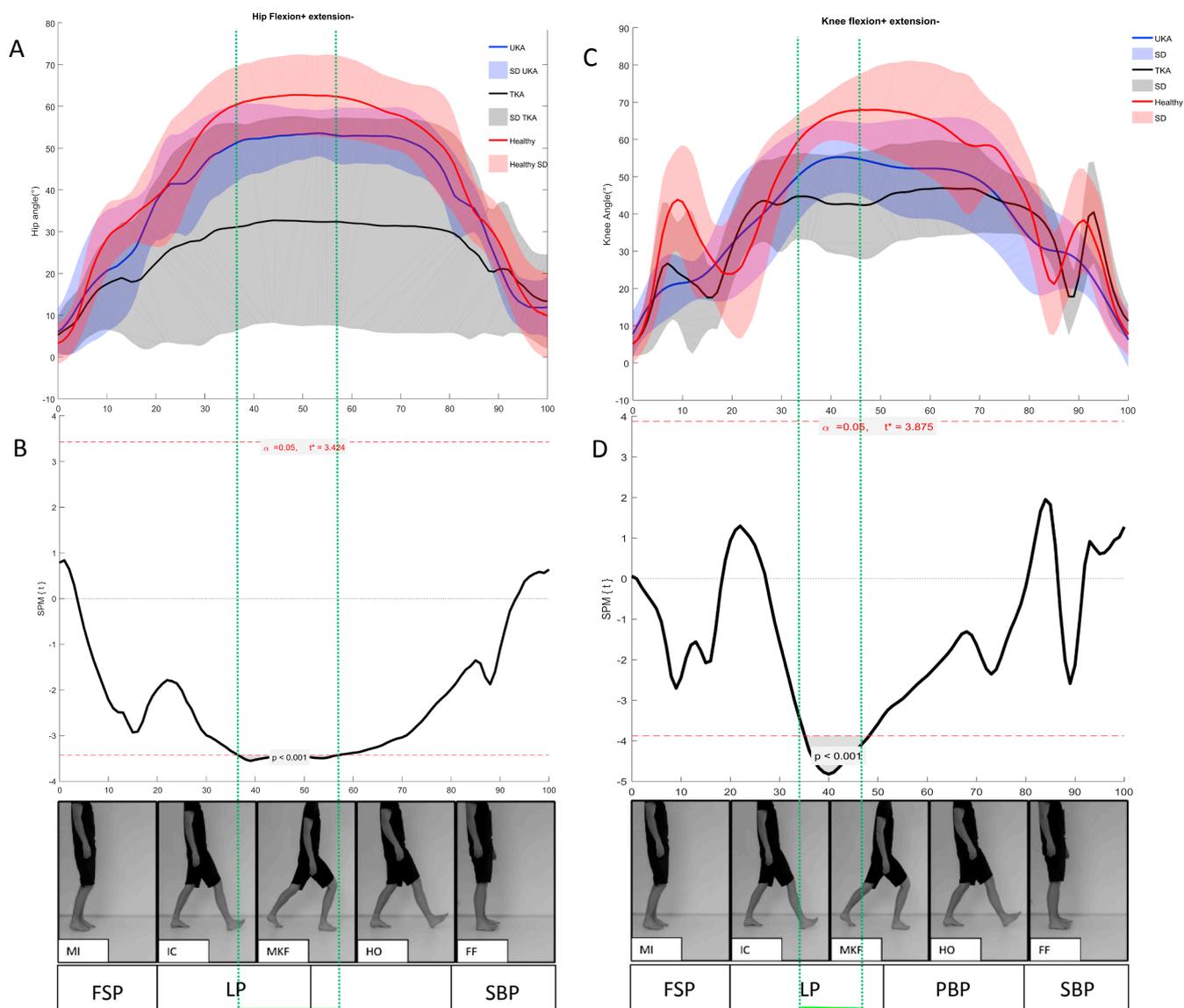
Fig. 4. Hip and knee sagittal kinematics.

lower gluteus maximus and hamstrings strength values at the arthroplasty side among patients with TKA compared to controls could have contributed to the poor performance observed in these patients. Moreover, the significantly lower quadriceps strength values observed in patients with TKA might have induced a quadriceps avoidance strategy, in which one tries to reduce the external flexor moment at the knee by reducing knee flexion angles [Gaffney et al., 2016].

The present study showed kinematic abnormalities during dynamic tasks among patients with knee total replacement, even up to one year after knee surgery. We suggest that, similarly to other populations [Alkjær et al., 2009, Mattacola et al., 2004, Wagenaar et al., 2011], the biomechanical performance of functional tasks such as the FL is related to the functional outcome of knee replacement patients. Since up to 20% of patients with a knee replacement remain dissatisfied with the results of their surgery, mainly due to difficulties encountered when performing activities of daily living, understanding the deviations in FL kinematics might contribute to better insight into the functional deficits after knee surgery.

Despite the uniqueness of this study, being the first to quantify hip and knee kinematics during forward lunge in TKA and UKA patients and age-matched controls, some limitations must be mentioned. Most importantly, the small sample size of the study warrants caution when

generalizing the results to the entire patient population. This study was designed as a pilot study to explore possible differences between TKA, UKA and control subjects. Yet, other studies reporting kinematic analyses based on SPM also reported similar sample sizes [Ardestani and Moazen, 2016; Goudriaan et al., 2018]. The strongly significant differences in hip and knee kinematics reported in this pilot study are important for the clinical evaluation of patients with a knee replacement and further research on this topic with inclusion of a larger number of patients is highly desirable. The high BMI observed among knee replacement patients could have affected the 3D kinematics obtained from the motion capture system [Lerner et al., 2014]. Yet, this study only reported hip and knee joint sagittal kinematics, which were shown to be reliable even in subjects with a high BMI [Callewaert et al., 2013].

5. Conclusions

This pilot study showed significantly reduced hip and knee joint angles during the forward lunge performance in patients with TKA compared to controls. These kinematic adaptations might be related to the absence of the cruciate ligaments, which is further supported by research demonstrating the essential role of these ligaments during the

forward lunge [Alkjaer et al., 2009]. Furthermore, the reduced muscle strength of the gluteus maximus, hamstrings and quadriceps muscles in patients with TKA also likely influenced the kinematics of the forward lunge. Future research should focus on the assessment of both kinetics and kinematics of the forward lunge at different time points following knee replacement surgery, as this could bring new insights into the functionality of patients with UKA and TKA.

Declaration of Competing Interest

Authors declare no conflict of interest.

Acknowledgements

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelekin.2019.06.002.

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