Sagittal knee gait changes after medial unicompartmental and total knee arthroplasty – an exploratory analysis of 36 patients

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Abstract

This study aimed to investigate postoperative developments of sagittal knee gait in a population of knee arthroplasty patients randomized to either unicompartmental or total knee arthroplasty. We hypothesized that knee arthroplasty patients develop greater walking speeds, range of motion, sagittal knee angle velocities, and sagittal knee angle accelerations. 36 patients were recruited from a randomized trial comparing the two implant types. Sagittal knee gait was examined preoperatively, four, and twelve months postoperatively. The examination used inertial measurement units. Nine gait parameters were defined focusing on knee angles, angular velocities, and accelerations. Stride frequency increased by 0.2 s^{-1}. Walking speed increased by 0.3 m/s. The range of motion increased by 7 degrees. Extension and flexion velocity during knee swing increased by 72 and 49 degrees/second. Acceleration during flexion increased by 565 degrees/second^2. Acceleration during extension increased by 1168 degrees/second^2. Acceleration after heel strike increased by 1549 degrees/second^2. We observed significant developments in sagittal knee gait after knee arthroplasty. Patients developed faster walking speed and greater stride frequency, as well as improvements in range of motion, sagittal knee angle velocities, and accelerations.

Introduction

Knee arthroplasty is a safe and effective treatment option for idiopathic knee osteoarthritis [1]. The incidence of patients suffering from knee osteoarthritis has been increasing rapidly over the last 20 years resulting in increasing rates of knee arthroplasty [1]. A study has projected a six-hundred percent increase in knee arthroplasty rates from 450,000 procedures in 2005 to 3.48 million procedures by 2030 in USA[2]. The decision for performing the procedure is made jointly by the patient and the knee surgeon depending on patients' symptoms and radiographic evidence of arthritis[1]. No clear consensus exists regarding exact indications as they are not completely objective but based on patients' own information and surgeons' interpretation of radiographic images [1].

Gait analysis can be used to assess knee function before and after knee arthroplasty. It provides a novel method for objectifying knee function [3–5]. The "gold standard" for gait analysis is advanced 3-D motion capture analysis technology [6], but these systems are costly and require a specialized laboratory. Inertial measurement units (IMUs) have been proven to be valid and in high agreement with motion capture technology while being cheap, mobile, and easy to use [7]. IMUs are increasingly realistic to use in a clinical setting.

A multicenter randomized double-blinded controlled trial of 350 patients aimed at investigating the patient-reported and clinical differences between unicompartmental knee arthroplasty (UKA) and total knee arthroplasty (TKA) is ongoing at our institution [8]. This exploratory study was initiated to explore the sagittal knee gait changes of these patients. The specific study aim was to investigate the developments of sagittal knee gait of randomized and blinded patients, receiving either UKA or TKA. We hypothesized that the patients achieve greater walking speeds, greater range of motion, faster and more powerful knee swings, measured in the sagittal plane. Gait analysis has the potential to offer new and meaningful data to surgeons when assessing the postoperative result following knee arthroplasty, which is the future perspective of this study.

Methods

Study design

This study was an exploratory study of the developments of sagittal knee gait following knee arthroplasty. Patients in this study were included prospectively from March 2018 to October 2020, The patients participated in an ongoing national multicenter double-blinded randomized controlled trial (RCT) [8]. The RCT is registered at clinicalTrials.gov (registration no. NCT03396640) and complies with the CONSORT guidelines [9,10]. All patients gave their written and information consent to both studies. The Danish Ethics Committee have approved the initiation and completion of the studies (approval nr. H-16037372). The STROBE guidelines were applied to this study. Only patients with radiographically and perioperative confirmed anteromedial-osteoarthritis were included. Patients were randomized during surgery to receive either cementless medial Oxford partial knee phase 3-alpha (UKA) or cemented TKA. The type of TKA used was the surgeons' preference. Regardless of the implant received, the same surgical approach was applied (midline incision). Measurements of gait took place 2 weeks before surgery, 4 months after surgery, and again 1 year postoperatively. Patients and the research group were blinded for implant type one year postoperatively. Only patients included at one of the participating hospitals were offered inclusion in this study.

Measurements

The patients were equipped with two IMUs (ISENS-100, Icura Aps, Copenhagen, Denmark) connected to a smartphone. One sensor was positioned at the lateral aspect of the proximal thigh and the other distally at the lower leg (Fig. 1). The IMUs were calibrated automatically and subsequently manually before measurements (using a goniometer), and recording was controlled by a custom-made app. The sagittal knee joint angle was measured with a nominal frequency of 20 hertz. Each sensor weighed 27 grams and its dimensions were 68x42x15 millimeter. The sensors consisted of an accelerometer, gyroscope, and magnetometer. Patients were first asked to walk for a six-minute familiarization period on the treadmill at level walking [11]. Patients were then asked to adjust the speed of the treadmill to their maximal walking speed, at which recording for data collection began. The duration of the recording used for analysis were 60 seconds.

Data analysis

In short, our algorithm used event landmarking for identifying the sagittal knee swings in our data (Fig. 2) [12]. The Lomb-Scargle algorithm was used to determine the stride frequency. Within each period, the maximal flexion was landmarked, and a Fourier series was used to fit the average gait cycle from raw data [13]. The Fourier series allowed easy calculation of first and second derivatives and integrals, which in turn allowed the calculation of angular velocity and acceleration. A more detailed description of our method is available in **Supplementary material.**

9 different gait parameters were calculated from the Fourier expansion (Table 1). We focused on spatiotemporal parameters (stride frequency, walking speed), range of motion, the average knee angle during a stride, angular velocity (maximum flexion and extension velocities), and angular accelerations (maximum flexion and extension acceleration during swing phase, and maximum flexion acceleration after heel-strike).

Table 1

An overview of calculated parameters from the average gait cycle.

	Parameter.	Unit of measurement and description
Spatiotemporal data		
	Stride frequency	Strides per second; A stride is defined as the point of maximal flexion in a swing, to the following point of maximal flexion in the next swing (s^{-1}).
	Walking speed	Meters per second
Angular data		
	Range of motion	Difference between maximal and minimal angle measured (in degrees). The amplitude corresponds to the angular range from maximal extension to maximal flexion. It is interpreted as the range of motion (ROM).
	Average knee angle	The area under the average gait cycle curve is divided by measurement duration. It is a measure of the average knee angle during the gait cycle.
Velocity data (1st derivative)		
	Maximal extension velocity during swing	The smallest value of angle velocity during the gait cycle. (angles/second). The highest angular speed of an extension movement.
	Maximal flexion velocity during swing	The largest value of angle velocity during the gait cycle. (angles/second). The highest angular speed of a flexion movement.
Acceleration data (2nd derivative)		
	Maximal flexion acceleration during a swing	The maximal acceleration measured during flexion in swing-phase (angles/second^2).
	Maximal extension acceleration during swing	The maximal acceleration measured during extension in swing-phase (angles/second^2).
	Maximal acceleration after heel-strike	The maximal acceleration measured after the heel strike during stance phase (angles/second^2).

Statistical analysis

Comparisons over time were done using a mixed effects model with a random subject specific effect to account for the correlation within subjects. Comparison of UKA and TKA patients were not performed due to the low sample size. P-values below 0.05 were considered significant. Models were validated considering the goodness of fit plots of the residuals, and in some cases, the models were fitted with and without outliers to check that results were robust. Normal distribution of parameters was investigated using exploratory statistics such as histograms and QQ-plots. The models were plotted to visualize developments of sagittal knee gait over time grouped by implant type and model summaries were presented in a table. We focused on regression coefficients because the focus of this study was to investigate the changes of sagittal knee gait over the observation period. All analyses were performed using R Statistical Software (v4.1.2; R Core Team 2021, URL: https://www.r-project.org/). We did not perform a power analysis before the initiation of this study because of its exploratory nature.

Results

Exploratory statistics revealed that the 10 outcome parameters were normally distributed. The number of patients included at our institution into the RCT was 86. Of these 86 patients, 36 patients (21 UKA and 15 TKA) accepted inclusion in the gait study and they all completed preoperative measurement. Following surgery 33 of the 36 patients completed 4-months measurements and 32 completed 1-year measurements (Fig. 3).

No considerable differences in patient demographics were found between the patients participating in the gait analysis when grouped by implant type. Also we did not find any considerable differences between patients participating in the gait analysis, the patients who declined participation in the gait measurements, and the population of patients participating in the RCT (Table 2). Therefore, we considered the groups to be comparable.

Table 2
Table of patient characteristics for patients participating in gait analysis, patients who declined participation, and all patients participating in the randomized trial (RCT).

Patient demographics				
	UKA (n = 21)	**TKA (n = 15)**	**Declined participation in gait study (n = 50)**	**All patients participating in RCT (n = 350)**
Sex (male : female)	15 : 6	8 : 7	26 : 24	185 : 165
Age (years)	68.1 ± 5.7	68.8 ± 5.7	63.76 ± 8.5	65.1 ± 7.4
BMI (kg/m^2)	28.6 ± 4.4	29.2 ± 3.6	28.87 ± 4.3	29.2 ± 4.4
Height (m)	1.7 ± 0.11	1.7 ± 0.1	1.8 ± 0.1	1.7 ± 0.1
Passive extension	124 ± 8	124 ± 12	123 ± 12	124 ± 12
Passive flexion	1 ± 3	3 ± 4	2 ± 3	1 ± 3
The values are indicated as means with standard deviation. For intergroup comparison, student’s t-test was used for age, BMI, and height. The chi-square test of independence was used for sex.				

Strides and walking speed

Stride frequency increased by 0.1 (p = 0.01) and 0.2 (p < 0.001) at 4 months, and 1 year postoperatively (Fig. 4 **and** Table 3). Walking speed increased by 0.2 m/s (p < 0.001) and by 0.3 m/s (p < 0.001) after 4 months and 1 year (**Fig. 5**).

Sagittal range of motion during walking

The sagittal range of motion of the gait cycle increased by 7 degrees (p < 0.001) after 1 year (Fig. 6). The average knee angle during walking (the sum of sagittal knee angles during a knee swing) increased by 2 degrees (p = 0.048) and by 4 degrees (p < 0.001) after 4 months and 1 year (**Fig. 7**).

Sagittal knee angle velocity during swing

The maximal sagittal extension velocity during swing increased significantly by 72 degrees/second (p < 0.001) after 1 year (Fig. 8**)**. The maximal sagittal flexion velocity during swing increased significantly by 49 degrees/second (p = 0.006) after 1 year (**Fig. 9)**.

Sagittal knee angle acceleration

The maximal sagittal flexion acceleration during swing increased by 565 degrees/second^2 after 1 year (p = 0.02) (**Fig. 10**). The maximal sagittal extension acceleration during swing increased by 1168 degrees/second^2 (p = 0.03) after 1 year (**Fig. 11**). The maximal sagittal flexion acceleration after heel-strike increased significantly by 1549 degrees/second^2 ($p < 0.001$) after 1 year (**Fig. 12**).

Table 3: Mixed effects model. Regression coefficients with corresponding confidence intervals and p-values are listed for each time and parameter. The p-values represent comparison of all patients (TKA and UKA patients) at the time of measurement with the preoperative measurement. Significant p-values are highlighted.

Timing of measurement	Number of patients	Stride Frequency (s^{-1})	Walking speed (meters/second)	Range of motion (degrees)	Average knee angle (degrees)	Maximal extension velocity during swing (degrees/second)	Maximal flexion velocity during swing (degrees/second)	Maximal flexion acceleration during a swing (degrees/second^2)	Maximal extension acceleration during swing (degrees/second^2)	Maximal acceleration after heel-strike (degrees/second^2)
Preoperative (intercept)	n = 36	0.8	0.9	44	16	207	207	1850	2782	2592
4 months	n = 33	0.1	0.2	2	2	22	16	122	395	610
Confidence interval p-value		0.02 - 0.1 (p = 0.01)	0.2 – 0.3 (p <.001)	-1 – 6 (p = 0.2)	0.06 – 4 (p = 0.048)	-5 – 49 (p = 0.1)	-8 – 41 (p =0.2)	-390 – 638 (p = 0.6)	-252 – 1046 (p = 0.24)	-218 - 1444 (p = 0.2)
1 year	n = 32	0.2	0.3	7	4	72	49	565	1168	1549
Confidence interval p-value		0.1 – 0.2 (p <0.001)	0.3 – 0.4 (p < 0.001)	4 – 10 (p <0.001)	2 – 6 (p <0.001)	44 – 100 (p <0.001)	25 – 74 (p = 0.006)	113 – 1159 (p = 0.02)	589 – 1902 (p = 0.03)	705 - 2398 (p <0.001)

Discussion

This study aimed to investigate pre- to postoperative changes in sagittal knee gait after unicompartmental and total knee arthroplasty nested in a blinded RCT. In our study population it was found that the patients developed faster walking speed with greater stride frequency, greater range of motion during walking, faster and more powerful knee swings. Previous studies have found that as gait improves postoperatively, so do the patient-reported outcome measures [14]. A study found a correlation between increasing WOMAC scores (a patient reported outcome score) and increasing values of walking speed and cadence, meaning that improvements in gait may be a clinically valid measure of knee-status [15]. Another study found that angular velocity increases dramatically following knee arthroplasty, which agrees with our findings [16]. Angular velocity and acceleration may be more informative expressions of improved knee kinematics following arthroplasty because patients with pain or instability of the knee are likely to reduce the amount of force exerted on their knee joint. This is in concordance with the hypothesis of other studies [17]. If the amount of force that is exerted on the knee joint is increased, the patient will likely have a greater sensation of pain. Angular velocity and acceleration may thus be the most sensitive parameters for assessing the sagittal knee gait function. We believe this to be the first study to investigate angular acceleration, using IMUs in a blinded and randomized population.

From the Figs. 4–12, UKA and TKA patients seem to develop equal improvements in gait over time. No statistical comparison was made in this study due to the low sample size making comparisons very insecure. In a systematic review, Nha et al. found no differences between the gait of the two groups except shorter stride length in the TKA group compared with the UKA group [18]. Our results are in agreement with this finding, as no obvious differences between the groups are discernible, although we did not test this. In general, studies comparing UKA and TKA have found similar clinical outcomes for the first 1–2 years [19–21]. Wiik et al. found that downhill walking gait may differ between UKA and TKA, as they found that patients with UKA walked faster than TKA patients when walking downhill. They hypothesized that this finding may be due to an intact anterior cruciate ligament in the UKA group (which is retained during surgery) [22]. The ACL is important for the proprioception of the knee, and its removal during insertion of TKA could be a confounding factor for differences in gait between UKA and TKA, which would be interesting to investigate in future studies.

Limitations

There were limitations to our study. The magnetometer in the sensor was vulnerable to magnetic interference, but steps were taken to ensure that no large metallic objects were adjacent to the sensors. A common limitation when using IMUs is measurement errors due to possible loosening of the sensors. An adhesive surgical tape was used to prevent these errors, but wobbling can still occur in patients with excess soft tissue on the hip [23]. No adverse events following application of the tape were reported from our patients. Another limitation was the low number of participants, which makes our study vulnerable to selection bias. However, we found no signs of disparity in age, height, BMI, or gender between the study population and the RCT population. As a result, we consider our sample population to be representative. In addition, the number of participants was regarded as sufficient in an exploratory study of this kind. Precise quantifications of forces were not possible with our design, as we used IMUs and not force plates. However, we focused on the measurement of differences over time.

Conclusion

In conclusion, we have reported pre- to postoperative changes in sagittal knee gait following knee arthroplasty. Parameters such as walking speed, range of motion, sagittal knee angle velocity, and acceleration increased significantly following the two types of knee joint arthroplasty. These increases are indicative of improved sagittal knee gait patterns. We found that UKA and TKA seem to develop equal changes in sagittal knee gait following surgery. Angular acceleration may be the most indicative parameter for assessing the sagittal knee gait function.

Declarations

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Author contributions

JH was the main investigator and was responsible for inclusion, measurements, data collection, data analysis, statistical analysis, and writing the article.

JM supervised JH in the overall study process and the article’s creation.

EG and LL assisted JH with inclusion and data collection.

AH was responsible for creating a second algorithm for data analysis, as part of the proofing process.

TS supervised JH with statistical analyses.

AO was the primary supervisor and creator of the study.

Data availability statement

Sharing of personal data collected from this study is not permitted to be shared outside the research-group. Anonymized results from the gait analysis are available from the corresponding author on reasonable request.

Competing interests statement

The authors declare that they have no competing interests.

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Figures

Figure 1

Placement of wearable sensors; immediately below the greater trochanter laterally, and immediately above the lateral malleolus. Picture is brought with consent of participant.

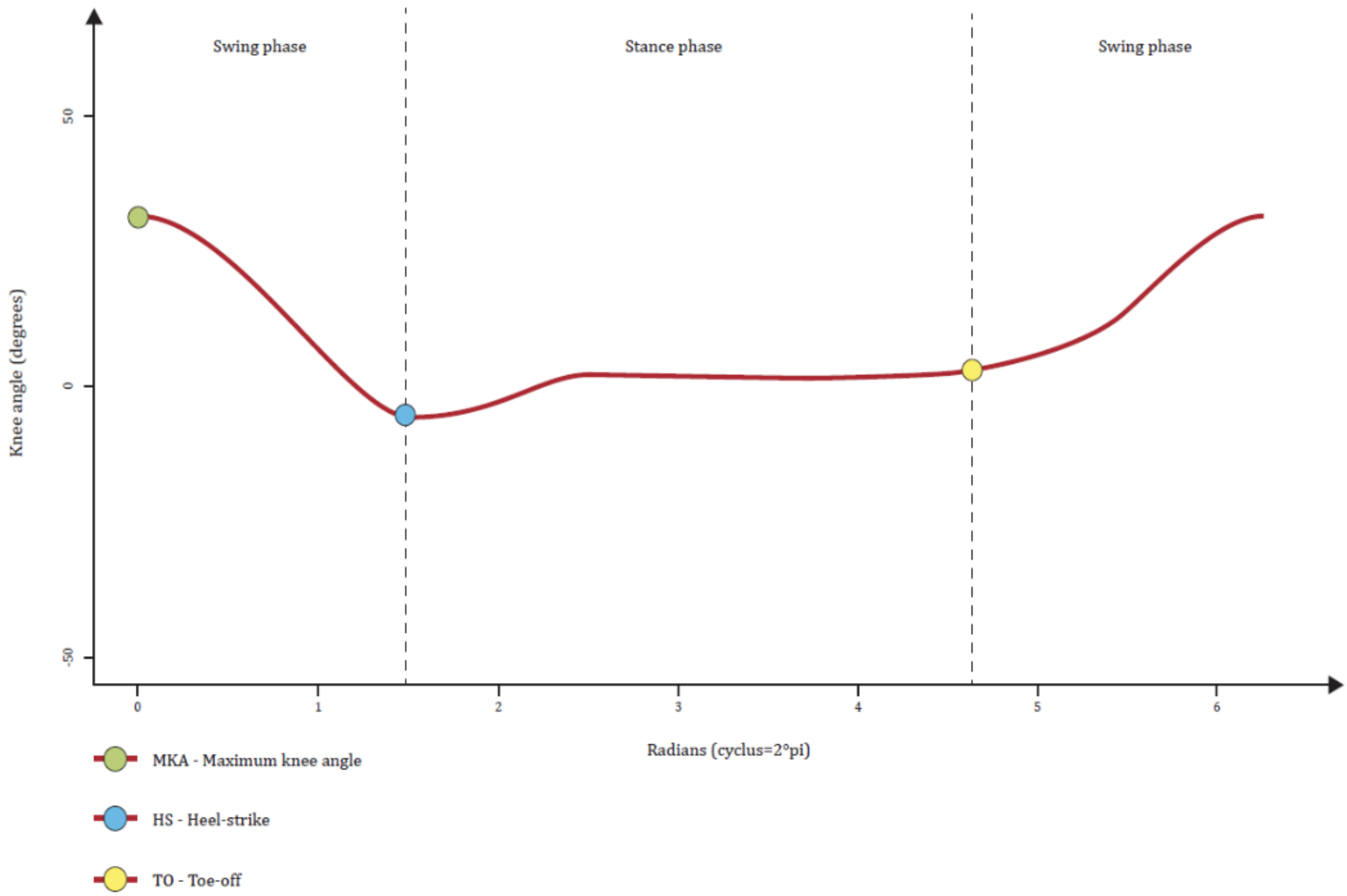

Figure 2

Graph of an average gait cycle for one data recording. Time is expressed on the x-axis and sagittal knee joint angles are expressed on the y-axis. The maximum knee angle marks the beginning of the gait cycle because it is an easily found landmark in all gait cycles. Swing- and stance phases are marked in the gait cycle.

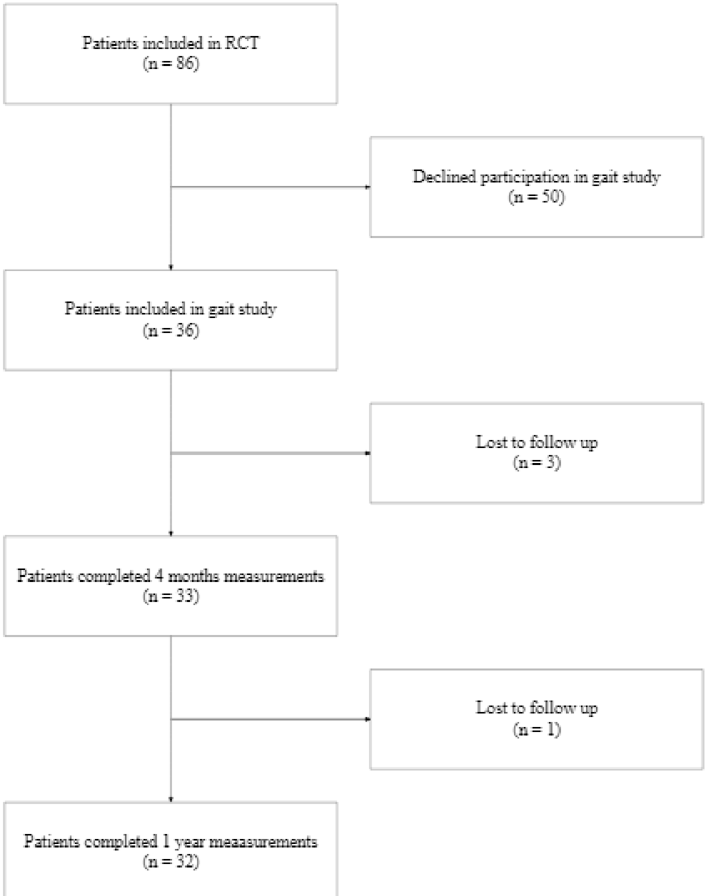

Figure 3

Flowchart depicting the process of inclusion, measurements, and loss to follow-up.

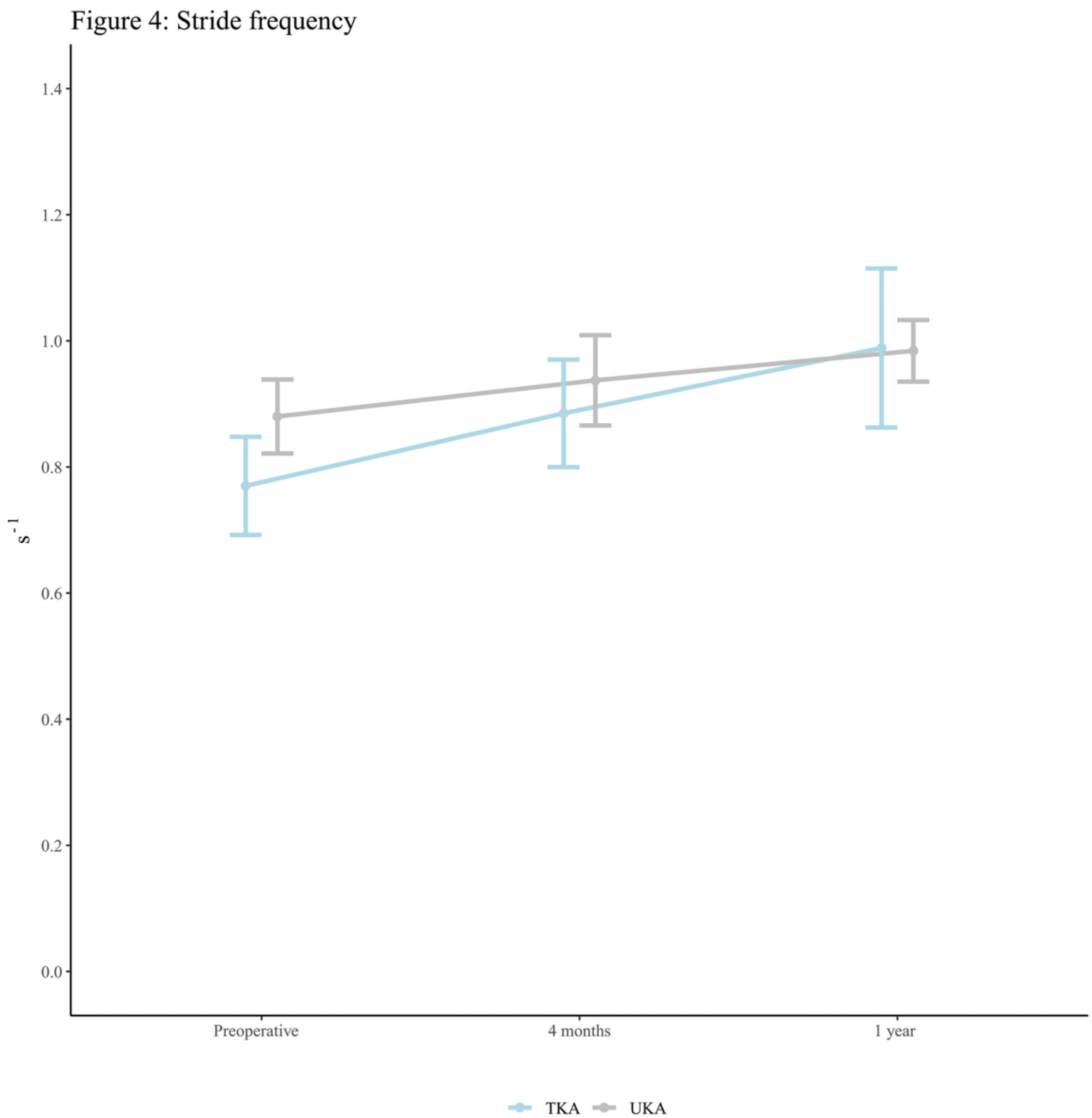

Figure 4

Plots of mean and 95% confidence intervals of stride frequency and walking speed.

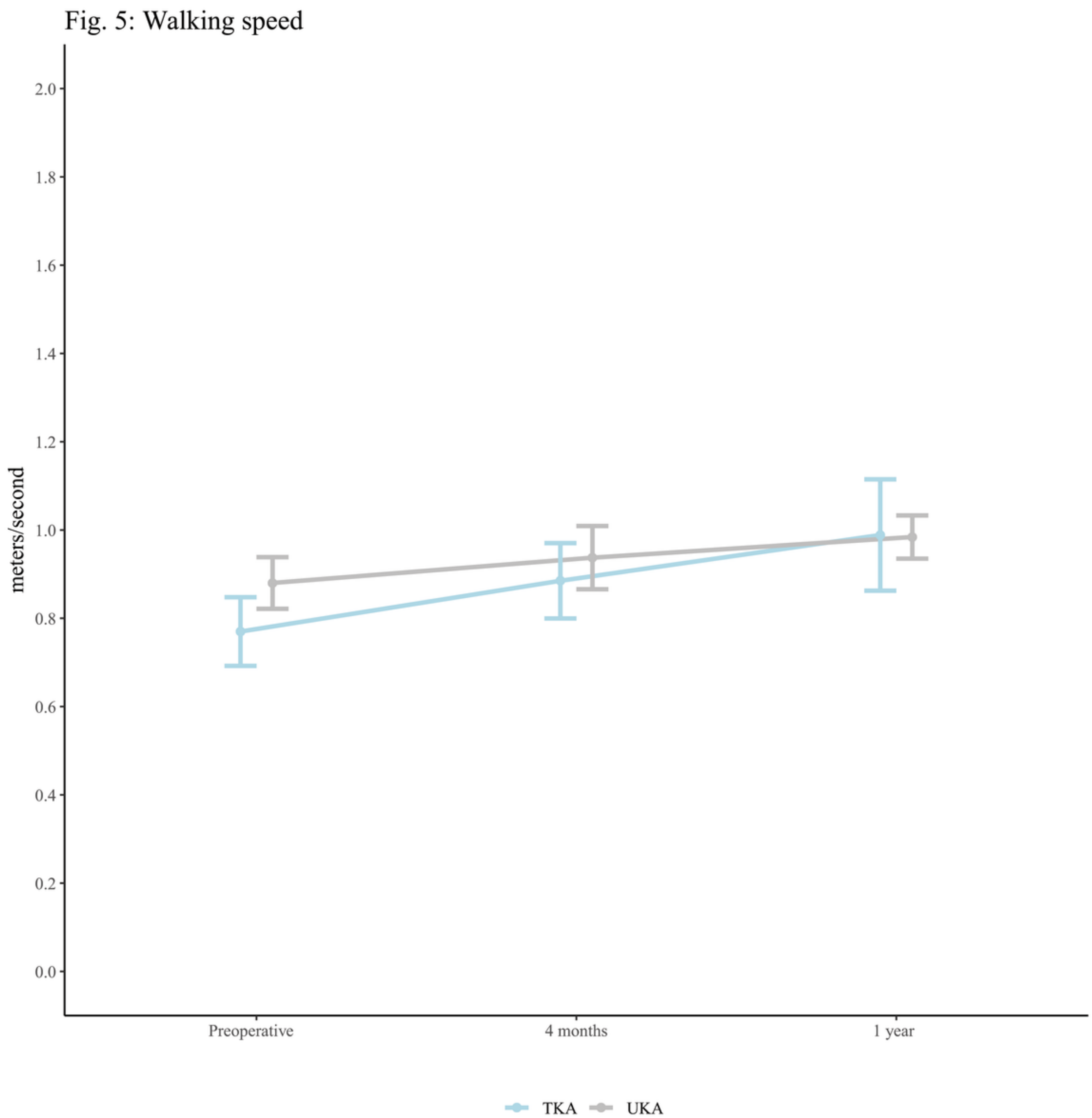

Figure 5

Plots of mean and 95% confidence intervals of stride frequency and walking speed.

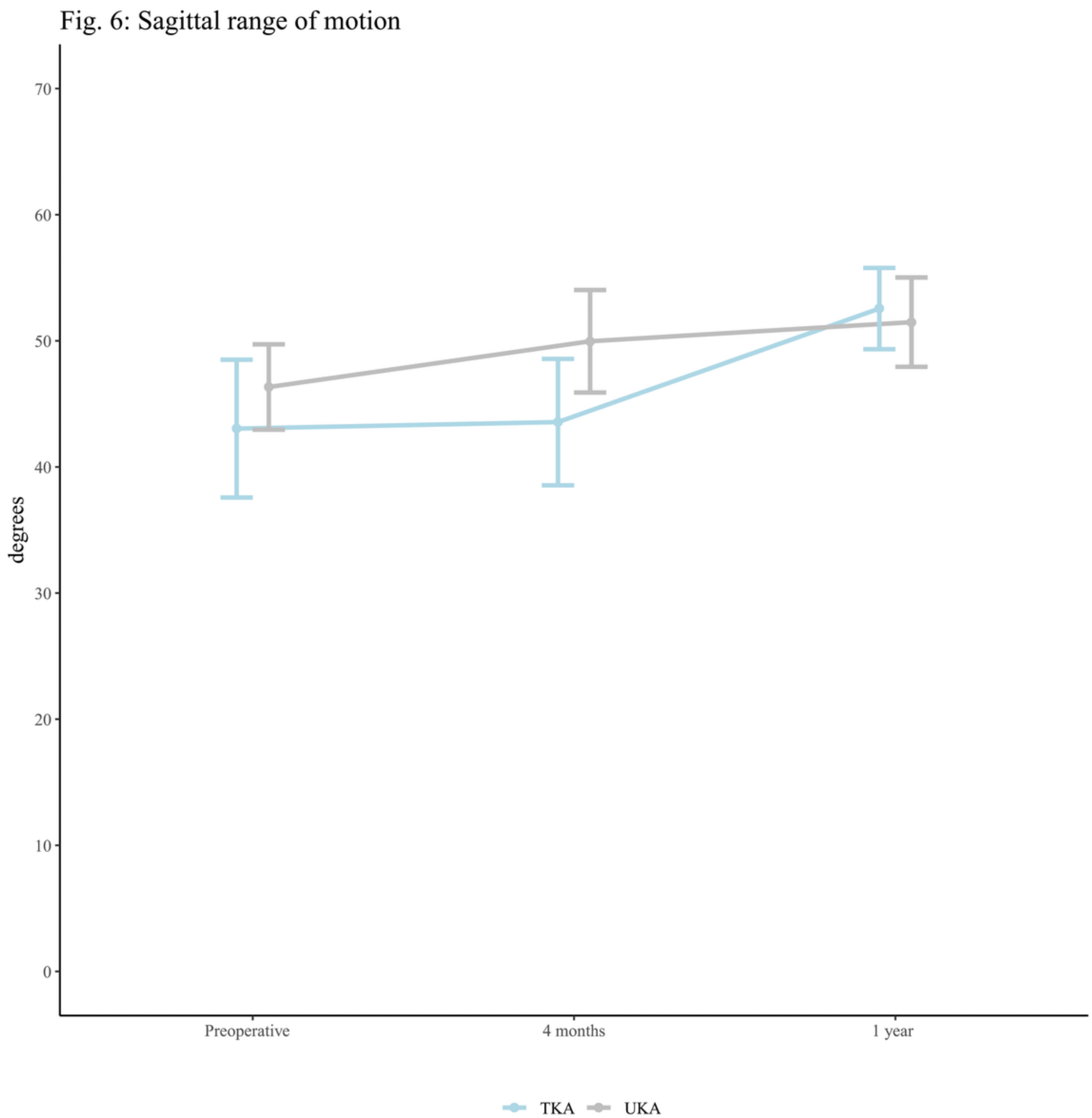

Figure 6

Plots of mean and 95% confidence intervals of the sagittal range of motion and average knee angle.

Fig. 7: Average knee angle

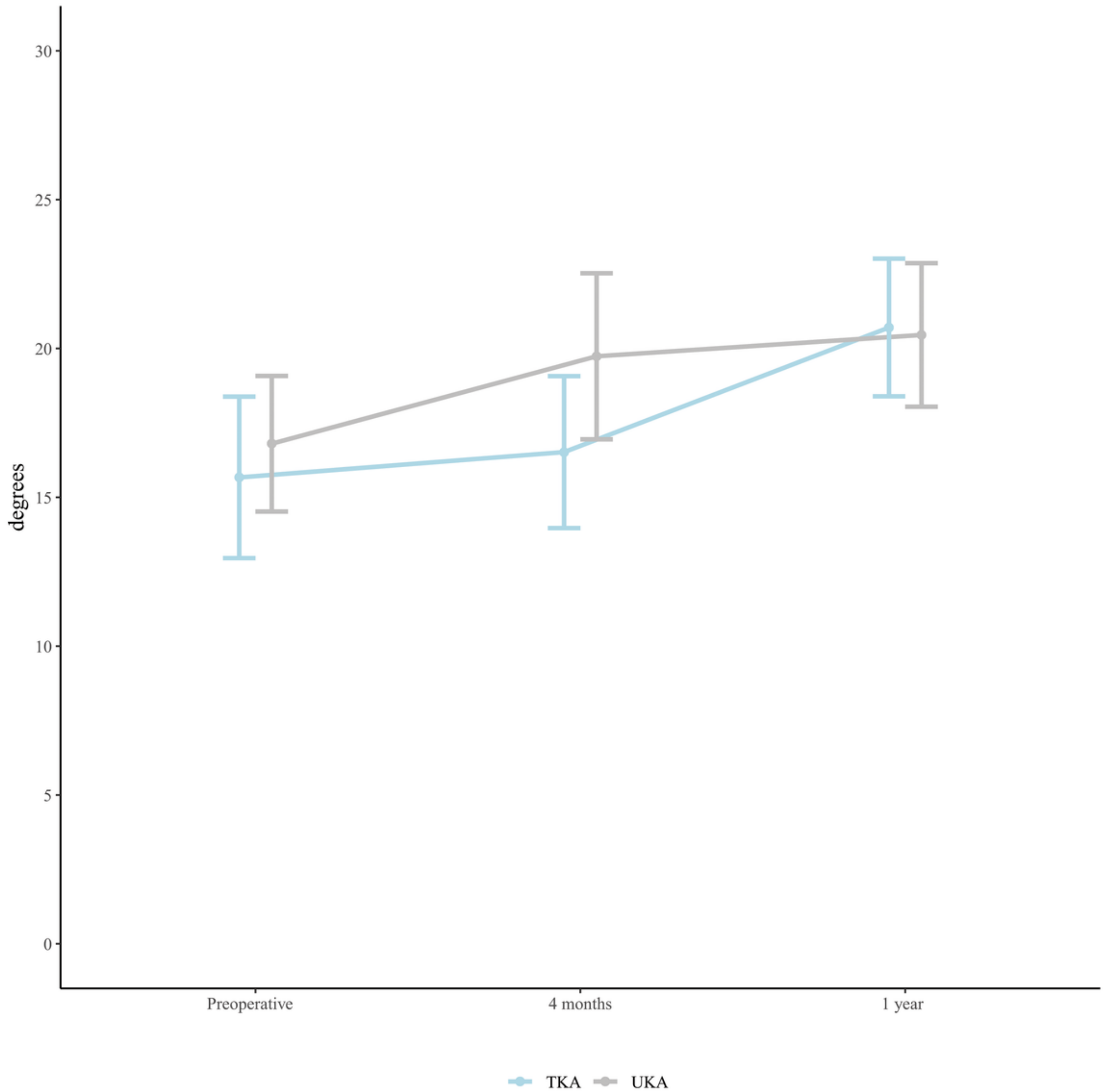

Figure 7

Plots of mean and 95% confidence intervals of the sagittal range of motion and average knee angle.

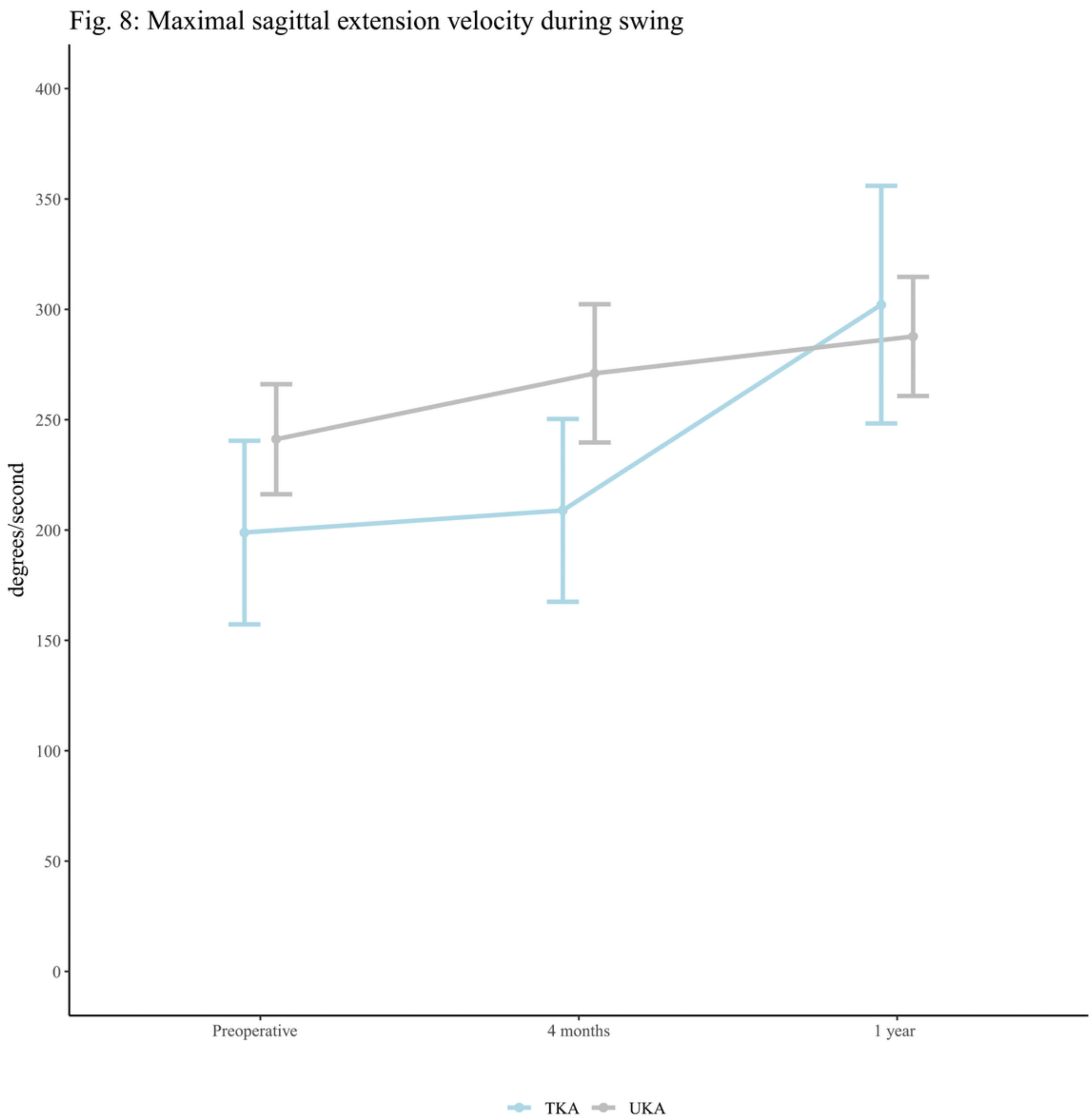

Figure 8

Plots of mean and 95% confidence intervals of the maximal sagittal extension velocity and the maximal sagittal flexion velocity during swing.

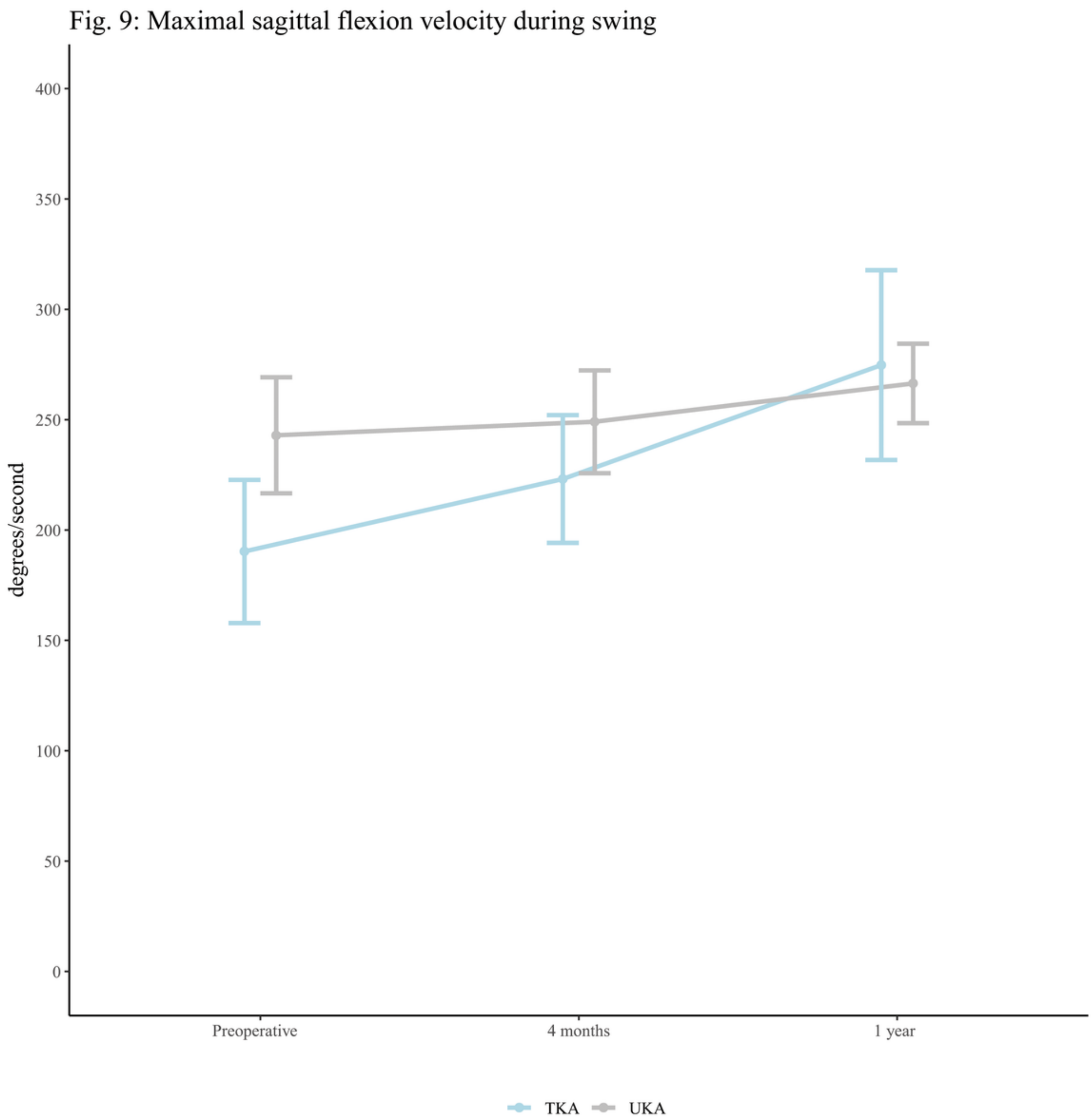

Figure 9

Plots of mean and 95% confidence intervals of the maximal sagittal extension velocity and the maximal sagittal flexion velocity during swing.

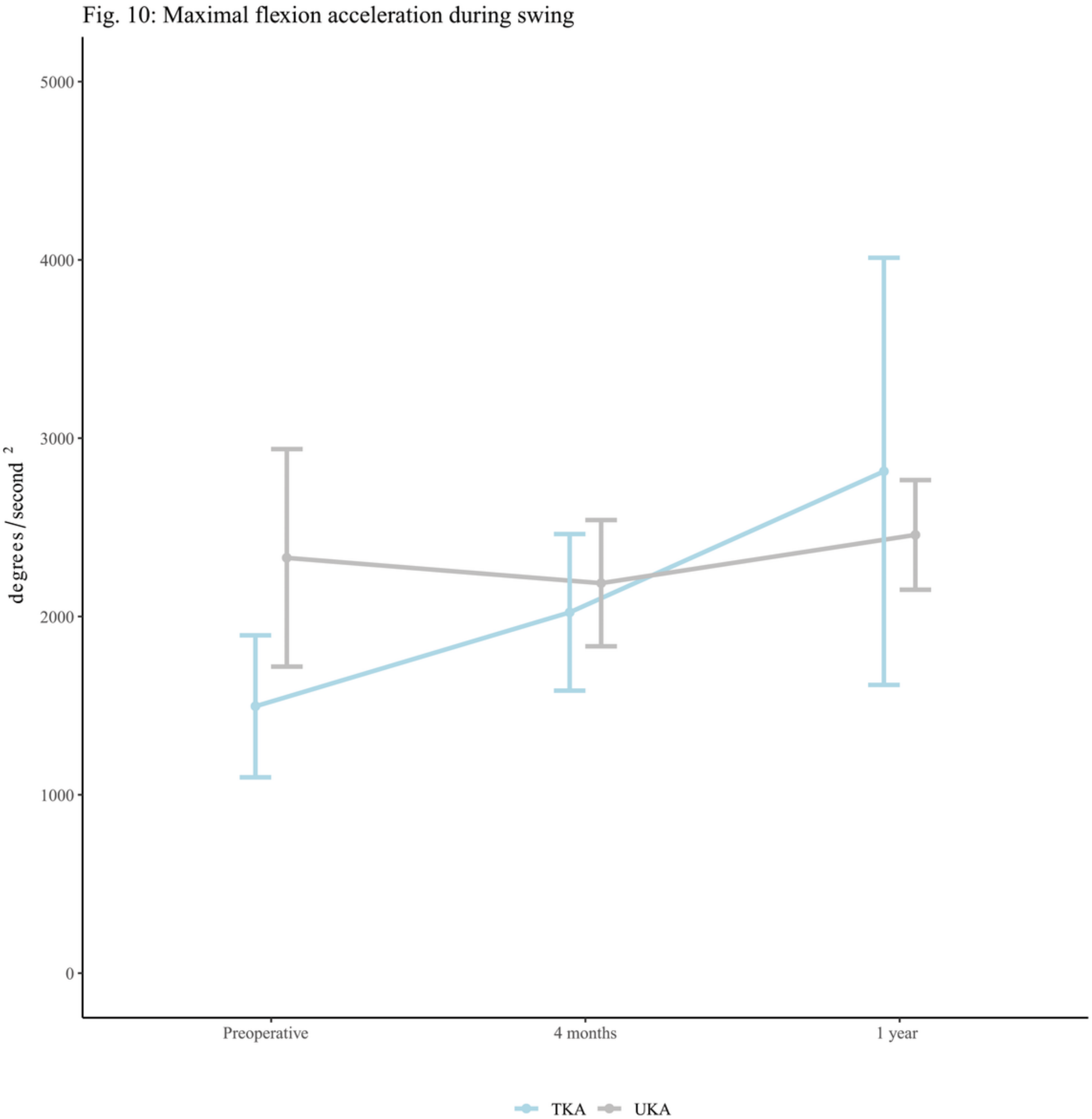

Figure 10

Plots of mean and 95% confidence intervals of the maximal flexion acceleration during the swing, the maximal extension acceleration during the swing, and the maximal acceleration after the heel strike.

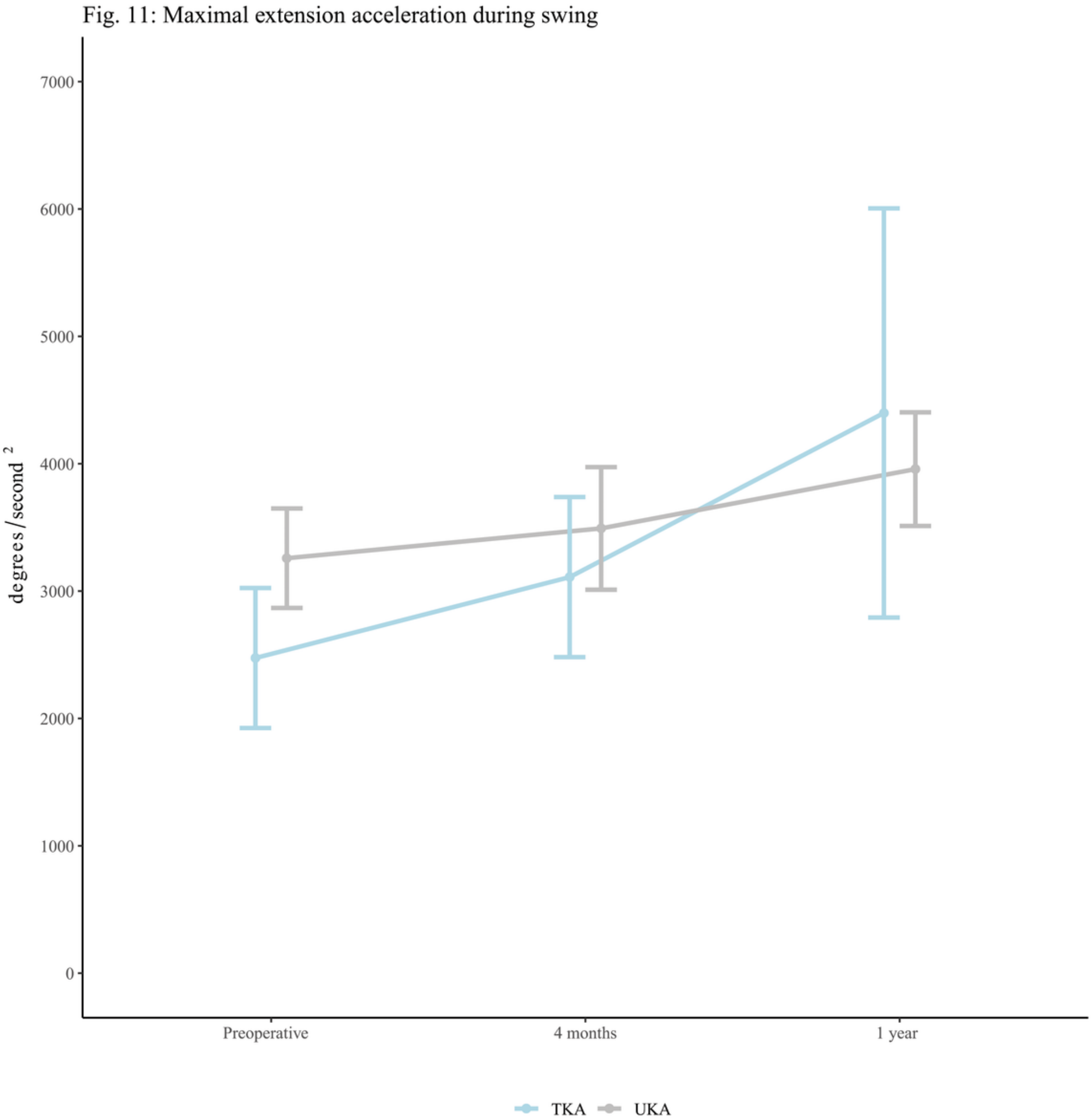

Figure 11

Plots of mean and 95% confidence intervals of the maximal flexion acceleration during the swing, the maximal extension acceleration during the swing, and the maximal acceleration after the heel strike.

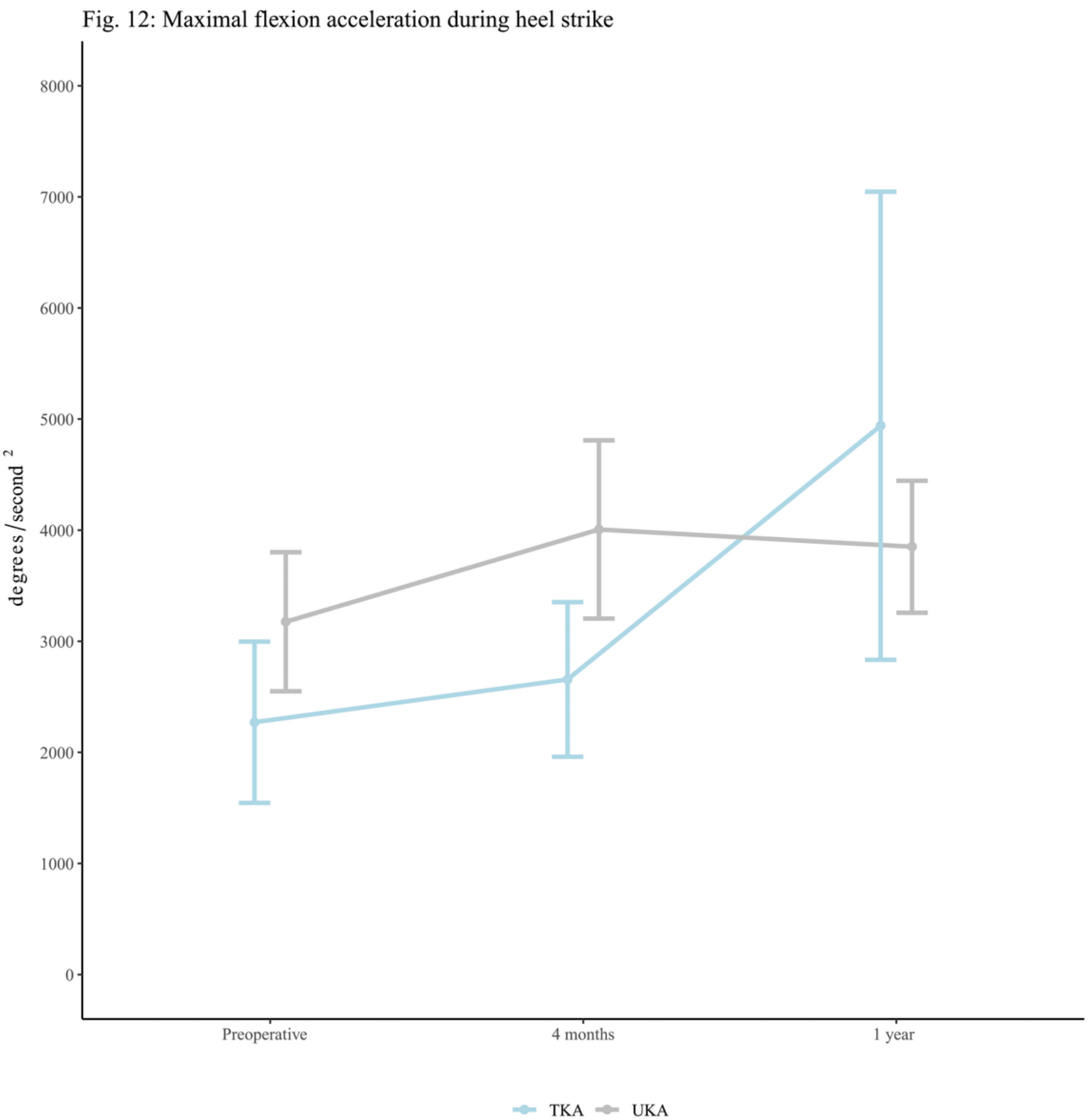

Figure 12

Plots of mean and 95% confidence intervals of the maximal flexion acceleration during the swing, the maximal extension acceleration during the swing, and the maximal acceleration after the heel strike.

Supplementary Files

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