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Can total knee arthroplasty restore the correlation between radiographic mechanical axis angle and dynamic coronal plane alignment during gait?

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ABSTRACT

Background: Total knee arthroplasty (TKA) is the treatment of choice for end-stage knee osteoarthritis. Postoperative static knee alignment has been recognized as a key component of successful surgery. A correction toward the kinematics of a native knee is expected after TKA, with an aim for neutral mechanical alignment. The evolution of frontal plane knee kinematics is not well understood.
Methods: Nineteen patients awaiting TKA were recruited. Three-dimensional knee kinematics during treadmill gait were assessed pre-operatively, 12 months after surgery, and compared to a control group of 17 asymptomatic participants.
Results: Mean radiographic mechanical alignment was corrected from 5.4° ± 5.0 (Standard Deviation) varus pre-operatively to 0.1° ± 2.0 (Standard Deviation) valgus postoperatively ($P = 0.002$). Mean stance coronal plane alignment decreased from 6.7° ± 4.0 (Standard Deviation) varus peroperatively to 2.1° ± 3.8 (Standard Deviation) postoperatively ($P = 0.001$). Correlation between radiographic mechanical axis angle and dynamic frontal plane alignment during gait, before and after surgery, was weak (pre-operative $R = 0.41$; postoperative $R = 0.13$) compared to control ($R = 0.88$). In the sagittal plane, TKA patients maintained their pre-operative stiff knee gait adaptation. Postoperative transverse plane kinematics suggested restoration of external tibial rotation during swing after TKA compared to control (Pre-operative 3.1°, postoperative 6.8°, control 7.1°, $P = 0.05$).
Conclusion: The lack of correlation between static and dynamic alignment suggests that static radiographic coronal alignment of the knee does not accurately predict dynamic behavior. In the sagittal plane, pre-operative gait adaptations were still present 12 months after surgery, supporting the need for a functional assessment to guide postoperative rehabilitation following TKA.

1. Introduction

Total knee arthroplasty (TKA) is the favored treatment for end-stage knee osteoarthritis (OA) when conservative therapies fail. It is well documented that the osteoarthritic knee population displays altered knee kinematics, more so in the coronal/frontal

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plane. In fact, varus alignment and varus thrust have been identified as mechanical markers for disease severity and key factors in disease progression [1,2]. Therefore, the goal of surgery is not only to replace degenerated cartilage surfaces but also to restore native knee kinematics. To do so, one key aspect of surgical planning is to address knee alignment. Through a static long film x-ray, the measurement of the two-dimensional hip–knee–ankle (HKA) angle makes it possible to assess the level of misalignment in the coronal plane and correct it. Although now being questioned, the gold standard objective of surgical planning is to aim for a neutral mechanical alignment of 0.0° ± 3.0 [3].

The success rate for TKA is known to be very good. Nonetheless, approximately 18% of patients report some level of dissatisfaction [4]. Surgical success is determined, in part, by proper implant positioning and lower limb alignment, which are assessed using postoperative radiographs. Patient improvement, in terms of quality of life and functional recovery, is evaluated through subjective reported outcomes, with significantly better results following surgical treatment [5,6]. However, recent studies have outlined significant functional limitations after TKA, even if patient-reported outcome measure scores were very good [7].

Kinematic assessment during gait has been found to give valuable information on knee function. Few studies have described post-TKA three-dimensional (3D) knee kinematics, and while results show improved kinematics, they are not up to the level of a healthy asymptomatic group [8].

Recent studies have demonstrated a reduction in knee adduction (surrogate of varus) peak angle during stance after TKA [9,10]. However, the ability of TKA to correct and maintain neutral frontal plane kinematics during gait has been questioned [11]. Published results in the sagittal plane are more abundant, reporting a persistent flexion contracture during stance phase [12–14], as well as a reduction in range of motion (ROM) after TKA surgery. A recent study found that an improvement in flexion ROM also improved patient quality of life [15]. There have been few studies on motion in the transverse plane, due to soft tissue artifacts. McClelland et al. found greater external knee rotation and less internal knee rotation for TKA patients when compared to controls [12].

Data are also scarce when looking at the correlation between the radiographic HKA angle and coronal knee kinematics. Mündermann et al. demonstrated a moderate correlation between radiographic coronal plane alignment (mechanical axis) and static standing coronal plane alignment, measured with motion capture technology, in a knee OA population ($R^2 = 0.54$; $P < 0.001$) [16]. Conversely, Rivière et al. found no correlation between static coronal plane alignment and coronal plane kinematics of postoperative TKA [17]. These studies suggest that the correlation between frontal plane static alignment and dynamic behavior might be altered by TKA surgery.

Therefore, it remains unclear whether TKA aiming at mechanical alignment leads to a gait frontal plane pattern with neutral behavior and if it restores the relationship between static and dynamic alignment. To that end, the present study analyzed 3D knee kinematics in a population who underwent TKA aiming to restore neutral alignment. It was hypothesized that knee kinematics would change after a TKA to be closer to native knee kinematics in all three planes, and that the correlation between radiographic and dynamic alignment would be improved after surgery.

2. Material and methods

2.1. Participants

After receiving approval from the research ethics committees, a total of 25 participants with knee OA and awaiting TKA were recruited. Informed consent was obtained for each participant. Surgeries were performed between 2012 and 2014 by a fellowship-trained orthopedic surgeon. In order to be included in the study, subjects were required to walk independently for at least 15 min on a split-belt treadmill. Participants were assessed twice: once before surgery and once 12 months postoperatively. Each assessment included the Knee injury and Osteoarthritis Outcome Score (KOOS) questionnaire [18], medical examination, full weight-bearing x-rays, and a 3D kinematic gait analysis.

A control group of 17 subjects with asymptomatic knees were recruited from the community, and gave informed consent. A single experienced orthopedic surgeon examined the participants of the asymptomatic group in order to rule out any symptomatic or asymptomatic knee pathologies.

2.2. Surgical technique

Every participant received either a posterior-stabilized or bicruciate-retaining primary TKA (Hermes, Ceraver-Osteal, Roissy, France). The same surgeon performed all surgical procedures. Varus knees were exposed using a standard anteromedial approach; valgus knees with an anterolateral approach. Distal femoral and proximal tibial cuts were performed using intramedullary and extramedullary guides, respectively, aimed perpendicular to the bone's mechanical axis. Femoral component sizing and rotation, and ligament balancing were integrated in a spacer-based gap-technique variant described in a previous study [19]. Tibial component rotation was set using the tibial tubercle and posterior edge of the proximal tibial cut as references. A standard inpatient physiotherapy protocol was initiated on the first postoperative day and continued after discharge with at-home visits.

2.3. Coronal plane mechanical axis

Knee frontal plane alignment was assessed using the HKA angle measured by the orthopedic surgeon on standard three-foot standing view x-ray films, both pre-operatively and postoperatively. The same three-foot standing view x-ray was also taken for the control group.

2.4. Three-dimensional kinematic evaluation

Three-dimensional kinematics of each participant were assessed using a 12-camera Vicon Motion Analysis System (Vicon, Oxford, UK). Participants were asked to walk on a split-belt treadmill at a self-determined, comfortable pace. Participants had a 10-minute adaptation period to get used to treadmill walking, find a comfortable pace, and ensure reproducible kinematics [20].

A validated knee marker attachment system (Figure 1) was used to reduce soft tissue artifacts and improve kinematic calculation (KneeKG, Emovi Inc., Canada). This device was chosen because it has been extensively validated in previous studies [21,22]. Fluoroscopic studies have shown significantly reduced relative movement between skin and bone for an accuracy of 0.4° in the frontal plane and 2.3° in the transverse plane during flexion/extension movements [12,13]. Furthermore, it provides repeatable (0.4–0.8° and 0.8–2.2 mm) and reliable (Intraclass correlation coefficient (ICC) 0.88–0.94) measurements of 3D knee kinematics [22]. A functional postural registration method was used to compute 3D anatomical angular displacement between the tibia and femur [21].

Kinematic computation and analysis were completed using a laboratory-developed MatLab function (MatLab, v2017a, Mathworks, Massachusetts, USA). The 3D knee kinematics were calculated using the convention described by Grood and Suntay [23]. Each gait cycle was defined using force plates embedded in the split-belt treadmill (Advance Medical Technology Inc., Watertown, MA, USA). Then, the 15 most repeatable cycles were chosen using a root mean square technique and kept to calculate mean patterns for each participant [24].

Kinematics were analyzed using specific points of interest during the gait cycle (such as knee angle at heel strike and toe off, and maximum angle during swing). The ROM during the loading phase, terminal stance, and total ROM during the gait cycle were also analyzed. Previous studies have associated these gait parameters with clinical outcomes [2,14,25–28].

Figure 1. KneeKG marker attachment (Emovi Inc., Canada).

2.5. Data analysis

A power calculation for the required sample size was based on a prior study that measured the abduction angle before and after TKA [11]. This study reported that the osteoarthritic population had a mean pre-operative abduction angle of 9.4° (standard deviation (SD) 6.5) during stance phase. In a previous study on TKA patients, the mean angle was 2.2° (SD 4.5) [29]. Therefore, the present study calculated that 17 subjects were needed in each group in order to obtain a power of 80% with a *P*-value of 0.05.

A Student *t*-test was used to compare the demographics between groups and assess mechanical axis correction pre-operatively and postoperatively. Since body mass index (BMI) has been shown to have an impact on kinematics, an analysis of covariance (ANCOVA) was used to control for BMI. Finally, a spearman correlation was calculated between the mechanical axis and dynamic alignment during gait. Statistical analysis was performed with Statistical Package for Social Sciences (SPSS) (IBM, New York, USA).

3. Results

Of the 25 participants in the surgical group, two were lost to follow-up. Four were excluded because of technical errors during data acquisition (calibration error or technical issues). Ultimately, a total of 19 surgical participants were included in this study. Demographic characteristics of the pre-operative and control groups were similar for age, gender and weight; however, height and BMI were different. Therefore, the control group, being taller and leaner in average height and BMI, was used as covariate. The demographic characteristics of participants are summarized in Table 1.

3.1. Evolution of the mechanical axis

Surgical planning for all the patients in this study aimed at restoring the mechanical alignment toward neutral (0.0° ± 3.0). This objective was successfully achieved (mean pre-operative HKA 5.4° ± 4.0 (Standard Deviation) (varus); mean postoperative HKA −0.1° ± 2.0 (Standard Deviation) (valgus) ($P = 0.002$).

3.2. Three-dimensional knee kinematics

The flexion angle at heel strike and at toe off did not differ between groups when controlling for BMI (see Table 2) (heel strike: pre-operative 16.0° (SD 7.0), postoperative 11.6° (SD 8.5), control 14.3° (SD 7.3), $P = 0.20$; toe off: pre-operative 9.0° (SD 8.0), postoperative 3.9° (SD 6.9), control 4.9° (SD 6.9), $P = 0.09$). Pre-operatively, participants demonstrated stiff knee gait, defined by a decrease in flexion ROM during loading phase, and a decrease in extension excursion during the end phase of stance, compared to the control group (Figure 2A). Surgery slightly improved extension ROM during stance, bringing it closer to the control group (extension ROM during terminal stance phase: pre-operative 8.8° (SD 4.9), postoperative 9.7° (SD 4.6), control 14.5° (SD 6.9), $P = 0.02$). Flexion ROM during the loading phase remained unchanged after surgery and, consequently, still differed from the control group (flexion ROM during loading: pre-operative 1.8° (SD 2.4), postoperative 1.9° (SD 2.3), control 5.1° (SD 3.9), $P = 0.004$).

Most of the pre-operative patient group walked with a dynamic knee alignment in varus. This alignment was maintained throughout the gait cycle (Figure 2B). Surgery restored the dynamic alignment to values closer to the control group (mean adduction (varus): pre-operative 6.7° (SD 4.0), postoperative 2.1° (SD 3.8), control 0.8° (SD 3.6), $P < 0.001$). The ROM in the frontal plane throughout the gait cycle was reduced postoperatively when compared to the pre-operative measurement and control group (pre-operative: 7.4° (SD 2.8), postoperative 5.9° (SD 2.8), control 8.6° (SD 3.1), $P = 0.009$).

Inter-individual variability for transverse tibial rotation was very high. Therefore, the mean pattern was similar pre-operatively and postoperatively, and for controls. It was observed (Figure 2C) that there was less external rotation pre-operatively during

Table 1
Participants' demographics.

Parameters	Pre-operative group		Control group		*P*
	N = 19		N = 17		
	Mean	(SD)	Mean	(SD)	
Age, years	60.8	(5.5)	56.7	(8.0)	0.076
Gender, M/F	7/12		11/6		0.10
Height, m	1.62	(0.08)	1.68	(0.10)	**0.045**[a]
Weight, kg	83.86	(14.76)	74.51	(15.64)	0.07
BMI, kg/m^2	31.93	(4.23)	26.17	(4.23)	<**0.001**[a]
Walking speed, km/h					
Pre	1.6	(0.87)	2.1	(0.92)	0.40
Post	1.8	(0.93)			

Abbreviations: SD, standard deviation;
BMI, body mass index.
[a] Statistical difference.

Table 2
Kinematic parameters.

Parameters	Pre-operative		Postoperative		Control		*P*
	N = 19		N = 19		N = 17		
	Mean	(SD)	Mean	(SD)	Mean	(SD)	ANCOVA
Sagittal plane							
Knee angle at heel strike	16.0	(7.0)	11.6	(8.5)	14.3	(7.3)	0.20
Knee peak angle during loading	17.8	(7.5)	13.6	(9.2)	19.4	(6.9)	0.10
Knee angle during toe off	9.0	(8.0)	3.9	(6.9)	4.9	(6.9)	0.09
Knee peak angle during swing	57.3	(8.2)	55.9	(9.5)	62.4	(7.2)	0.13
Knee flexion excursion during loading	1.8	(2.4)	1.9	(2.3)	5.1	(3.9)	**0.004**[a]
Knee extension excursion during stance	8.8	(4.9)	9.7	(4.6)	14.5	(6.9)	**0.02**[b]
Frontal plane							
Knee adduction angle at heel strike	6.5	(3.8)	1.7	(3.9)	1.4	(4.1)	**0.001**[c]
Mean knee adduction during stance	6.7	(4.0)	2.1	(3.8)	0.8	(3.6)	<**0.001**[c]
Knee peak angle during swing	8.5	(3.7)	3.8	(4.2)	3.9	(3.8)	**0.003**[c]
Knee adduction movement during loading	1.3	(0.8)	1.0	(0.9)	0.8	(0.7)	0.14
Total knee adduction range of motion	7.4	(2.8)	5.9	(2.8)	8.6	(3.1)	**0.009**[d]
Transverse plane							
Knee angle at heel strike	0.6	(2.6)	1.9	(2.7)	2.4	(4.2)	0.34
Knee external rotation during swing	3.1	(4.1)	6.8	(4.7)	7.1	(6.0)	**0.05**[b]
Knee internal rotation excursion during loading	2.7	(1.9)	2.2	(1.6)	3.6	(2.5)	0.23
Knee rotation range of motion	8.8	(3.5)	10.0	(5.5)	11.5	(4.4)	0.14

ANCOVA, analysis of covariance; SD, standard deviation.
Bold values means statistical different.
[a] Pre-operative and postoperative different to control.
[b] Pre-operative different to control.
[c] Pre-operative different to postoperative and control.
[d] Postoperative different to control.

swing phase. This pattern was corrected with surgery (maximal external rotation: pre-operative 3.1° (SD 4.1), postoperative 6.8° (SD 4.7), control 7.1° (SD 6.0), $P = 0.05$) (Table 2).

3.3. Coronal static and dynamic alignment correlation

The control group showed a strong correlation between radiographic HKA angle and mean frontal plane angle during the stance phase of their gait (*R* spearman coefficient of 0.88 and *R* square = 0.77, $P < 0.001$). The HKA angle was also correlated with frontal plane alignment at heel strike and toe off of the gait cycle, with *R*-values of 0.83 and 0.6, respectively. The HKA angle in the osteoarthritic group presented a weak or an absence of correlation with frontal plane kinematic parameters, with *R*-values ranging between 0.16 and 0.49. At the 12-month follow-up post-TKA surgery, no correlation was found between static and gait dynamic coronal alignment (Figure 3).

4. Discussion

Total knee arthroplasty is a well-accepted treatment for end-stage knee OA. Surgical success is generally assessed with static radiographs and patient-reported outcome measures. Nevertheless, a number of patients report an artificial knee sensation when walking after surgery, which often cannot be explained with the above-mentioned instruments. Therefore, 3D knee kinematic measurements are increasingly being used in order to gain a better understanding of surgical impact on knee kinematics and function. In the present study, a mechanical axis in neutral alignment (0.0° ± 3) post-TKA was aimed for and achieved in all patients. That correction can be measured on plain x-rays, has been well studied, and is thought to improve implant longevity [3].

The present study shows that TKA improves knee kinematics during gait when compared to pre-surgery. However, the results also show that kinematics are not restored to native knee kinematic levels. Pre-operatively, kinematic assessment revealed that patients displayed stiff knee gait patterns with a loss of flexion during the weight-acceptance phase, and a loss of extension during terminal stance of the gait cycle. Stiff knee gait was still present 12 months after TKA. Interestingly, previous authors have reported that one of the main factors affecting postoperative knee kinematics is pre-operative knee kinematics [30–32]. More specifically, a previous study [14] showed that pathological gait in an osteoarthritic population was characterized by an increase in the flexion angle during heel strike (contracture), fixed flexion throughout the stance phase, and decreased flexion maximums (loading and swing). In the current patient population, all these kinematic factors were present during pre-operative assessment and did not change at postoperative assessment. Therefore, it appears that replacing the articular surfaces and correcting the coronal plane did not address the adaptive gait strategies developed chronically by the osteoarthritic patient group, namely: flexion/extension contracture and loss of ROM in the sagittal plane. This gait pattern is seen in the osteoarthritic population because it helps stabilize the knee, and reduces shocks and forces that cause pain in the native knee [10]. Theoretically, forces and shocks

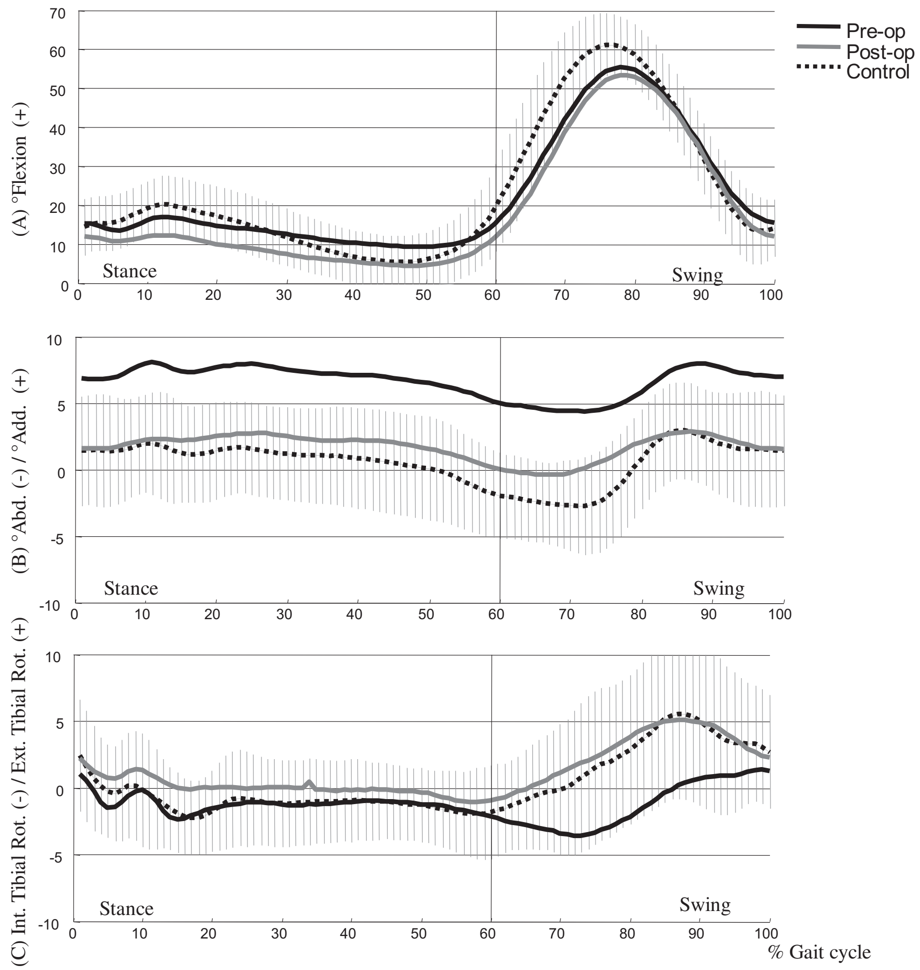

Figure 2. Group mean three-dimensional kinematics graph. A) Sagittal plane; (B) frontal plane (Abd = abduction, Add = adduction); (C) transverse plane (Int. Tibial Rot. = internal tibial rotation, Ext. Tibial Rot. = external tibial rotation). Only the Standard Deviation of the control group is shown to lighten the graph.

in the knee should not cause pain after TKA. This is why some authors report that adopting an abnormal gait pattern preoperatively could persist and never be corrected after TKA [30,31,33]. Recent studies have suggested using gait assessment to guide postoperative rehabilitation, and developed strategies to improve mobility in these patients [34]. The current results support this clinical need.

An important finding of this study is the ability of TKA surgery to restore frontal plane kinematics. The adduction angle at heel strike, mean adduction angle during stance, and peak adduction angle during swing all showed improvement, and moved closer toward native knee kinematics. However, the total coronal ROM during gait decreased after surgery and was found to be smaller than in the control group. Orishimo et al. questioned the ability of TKA to correct frontal plane kinematics [11]. In their study, patient frontal plane kinematics were corrected at six months after TKA, but by one year the kinematics returned to preoperative status. In the present study the frontal plane kinematics at one year remained close to native knee kinematics.

Three-dimensional gait analysis, especially in the coronal and transverse planes, has rarely been studied after TKA. This is mostly due to the low accuracy and reliability of classic measurement techniques in these planes. Soft tissue artifacts are a major contributor to this lack of reliability. Traditional gait analysis with markers positioned directly on the skin has been shown to produce a non-negligible error in the estimation of bone movement in the frontal and axial planes [35]. To reduce this error, a validated exoskeleton, was used [22].

Due to high inter-patient variability in transverse plane kinematics, the number of patients evaluated for transverse tibial rotation was too small to reach a power of 0.8, which could have limited the current conclusions. However, a similar external rotation pattern was noted during swing phase between the TKA and control groups. This observation supports the frontal plane kinematic results. Furthermore, the correction in transverse tibial rotation toward the control group would indicate that the results of frontal plane kinematics were not due to cross talk.

Another key finding of the current study was the correlation between frontal plane kinematics and mechanical axis on x-ray. In a population with no knee pathologies, there was a strong correlation between the mechanical axis on radiograph and various

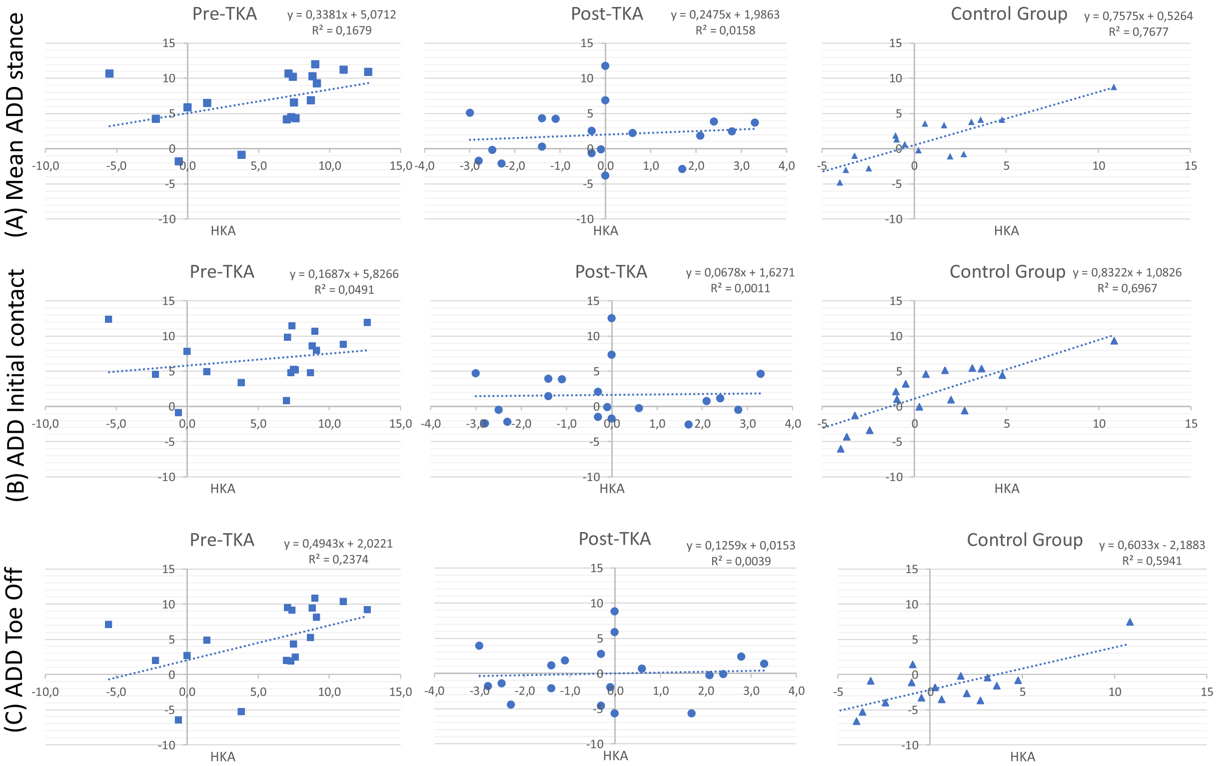

Figure 3. Correlation between hip-knee angle (HKA) and dynamic coronal alignment. (A) Mean adduction (ADD) during stance: Spearman in the pre-operative group (0.60), postoperative group (0.10), and control group (0.83); (B) adduction at initial contact: Spearman in the pre-operative group (0.40), postoperative group (0.06), and control group (0.81); (C) adduction at toe off: Spearman in the pre-operative group (0.62), postoperative group (0.10), and control group (0.61).

dynamic axes during gait ($R =$ between 0.77 and 0.88). Mündermann et al. published a similar correlation ($R = 0.74$) in an osteoarthritic population in a standing posture [16]. Interestingly, they reported a stronger correlation in the subgroup of patients with a low Kellgren–Lawrence score. The correlation with pre-operative patients in the current study was lower ($R = 0.41$) than reported by Mündermann et al. This could be partly explained by the severity and more advanced stage of OA found in the current participants and by the type of correlation assessment, which was based on dynamic measures. When the participants were re-assessed 12 months after surgery, no correlation was found between the x-ray and dynamic alignment during gait ($R = 0.13$). This goes against the initial hypothesis that surgery would improve both kinematics and correlation between static and dynamic alignment. In a recent study, Rivière et al. found a similar result after surgery, with correlation values of $R = 0.14$ [17]. It is believed that the current study is the first to prospectively assess the correlation of the coronal static–dynamic relationship and to compare it to a control group. Results show that the correlation between radiographic alignment and dynamic measurements during gait is strongly correlated in normal asymptomatic knees. However, this relationship decreased with the progression of OA and disappeared after TKA surgery.

The lack of correlation after surgery may be multifactorial. Although mean frontal kinematic parameters were improved postoperatively, kinematic variability between patients may cause correlation values to drop. This suggests that patients do not functionally adapt the same way after knee replacement and that monitoring gait kinematics after surgery would be beneficial. Further, the shape of the femoral implant condyle and the implant axial alignment may also impact frontal plane kinematics.

These findings strengthen previous studies showing that dynamic varus/valgus movement during gait can change after TKA in a way that static measurements cannot predict. They also add to the debate of whether the goal of surgery should be neutral static alignment or restoration of 'native' knee kinematics.

This study had some limitations. First, two implant designs were used in the surgical group. Patients who were treated with different implants were combined and analyzed as a single group. This limited the conclusions on the impact of the design itself; however, this was not the purpose of the study. The slow walking speed could also be perceived as a limitation. Previous studies have shown that walking speed has a direct impact on knee kinematics [12,36]. Participants in the current study were asked to walk at a self-selected comfortable pace; the goal was to reproduce an everyday situation. However, there was no statistical difference in the walking speed between the three groups; therefore, the effect of this limitation was likely minimal when assessing the impact of surgical treatment. Finally, in gait analysis studies, soft tissue artifacts are known to be a major source of error. In the current study, multiple tools were used to reduce these: the KneeKG exoskeleton, rigid body analysis, and analyzing the 15 most repeatable gait cycles measured during a 45-second walk on the treadmill.

5. Conclusions

The purpose of this study was to describe the impact of a neutrally aligned TKA on 3D knee kinematics. After knee arthroplasty surgery, 3D knee kinematics remained different compared to a control group. The main gait adaptation of a knee dynamic flexion contracture during stance phase found pre-operatively in the sagittal plane was maintained postoperatively. In the frontal plane, knee kinematics and static coronal alignment were corrected toward neutral alignment. However, the relationship between the two measurements, which was weak pre-operatively and became non-existent postoperatively, was strongly correlated in native knees. Further, TKA seemed to restrict ROM in the frontal and sagittal planes. Even with a small study group, a postoperative tendency toward decreased tibial internal rotation excursions during loading was observed.

This suggests that more needs to be learned on the static and dynamic alignment relationship. The authors believe that future studies should include this type of analysis when assessing the impact of surgical planning, patient satisfaction after TKA, and when monitoring post-surgery rehabilitation.

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All participants gave their informed consent to part of the study.

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