Scientific Research Publishing

Journal of Biosciences and Medicines, 2024, 12, 328-338
https://www.scirp.org/journal/jbm
ISSN Online: 2327-509X
ISSN Print: 2327-5081

Gait Kinematic Analysis Facilitates Rapid Early Recovery Following Total Knee Arthroplasty

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How to cite this paper: Liu, S.L., Cao, Z.Y., Lan, S.J., Zhang, C.J., Pan, L., Luo, W.J. and Li, J. (2024) Gait Kinematic Analysis Facilitates Rapid Early Recovery Following Total Knee Arthroplasty. *Journal of Biosciences and Medicines*, **12**, 328-338.
https://doi.org/10.4236/jbm.2024.1210028

Received: September 14, 2024
Accepted: October 21, 2024
Published: October 24, 2024

Abstract

Objective: To explore gait kinematics analysis and evaluate the surgical efficacy of total knee arthroplasty (TKA), as well as its guiding significance for postoperative rehabilitation. **Method:** Fifty patients admitted to TKA treatment for knee osteoarthritis from December 2022 to July 2023 were included, which were divided into an intervention group (gait kinematics analysis group, n = 25) and a control group (conventional rehabilitation program group, n = 25). All patients underwent HSS score and KSS score before surgery (T0), 1 month after surgery (T1), 3 months after surgery (T2), and 6 months after surgery (T3). The intervention group underwent gait kinematics analysis at 1 month after surgery (T1) and 3 months after surgery (T2). Two groups measured the hip knee ankle angle (HKA), distal femoral lateral angle (LDFA), and proximal tibial medial angle (MPTA) on knee joint radiographs before and after surgery. **Results:** There was no significant difference in general information, preoperative imaging parameters, and functional scores between the two groups of patients. There was no significant difference in functional scores and postoperative prosthesis alignment between the two groups of patients in the first month after surgery. The intervention group showed a significant decrease in gait kinematic scores in the first month, with hip joint scores being particularly prominent ($P < 0.05$). After two months of personalized outpatient intensive rehabilitation training, the intervention group showed significant improvement in gait kinematics scores by the third month, and both functional scores continued to improve. Moreover, the functional scores of the intervention group were better than those of the control group ($P < 0.05$). After three months of rehabilitation exercise, there was no significant difference in functional scores between the two groups at the sixth month ($P > 0.05$). **Conclusion:** Gait kinematic analysis is helpful in evaluating the postoperative efficacy of TKA and can guide early and rapid recovery after TKA.

Keywords

Gait Kinematic Analysis, Total Knee Arthroplasty

1. Background

Total Knee Arthroplasty (TKA) is a critical intervention for treating end-stage knee osteoarthritis, serving as the primary clinical approach to alleviate pain, correct deformities, reconstruct joint function, and enhance the quality of life of patients. However, dissatisfaction with postoperative outcomes exists among 19% - 60% of patients [1] [2], with postoperative knee kinematics being a significant factor for dissatisfaction following TKA [1]. As a result, post-operative knee kinematics have become a primary concern for both physicians and patients. Factors affecting postoperative kinematics in TKA patients include extrinsic joint factors (such as preoperative range of motion, obesity, underlying diseases, lumbar spine disorders, radiculopathy, neuroma, reflex sympathetic dystrophy) as well as intrinsic joint factors (including prosthesis design and selection, flexion-extension gap balance, alignment, prosthesis size and positioning, soft tissue impingement, and abnormalities in the extensor mechanism). While extra-articular factors can generally be addressed preoperatively, intra-articular factors typically require evaluation through imaging techniques such as X-ray, CT, MRI, and various scoring systems. However, conventional imaging evaluations usually only provide a snapshot of the knee joint at the time of examination, reflecting its two-dimensional morphology. Although dynamic X-rays combined with CT modeling have recently emerged as a highly precise method for dynamic measurement, their high cost and technical complexity have limited their widespread clinical application. Additionally, commonly used clinical scoring systems for assessing knee joint function after TKA are inherently subjective, and it is challenging to avoid bias in the evaluation of the patient's postoperative knee-related conditions. Therefore, it is particularly important to objectively, accurately, and dynamically evaluate the postoperative recovery of knee function [3].

Currently, knee kinematic analysis systems have evolved to include multiple modalities for collecting and analyzing knee kinematics data, such as dynamic CT, MRI, infrared 3D simulation, and gait analysis. Schmitz *et al.* [4] have utilized a single-camera, markerless method to gather lower extremity kinematics data; however, due to the complexity of the related technology, it has not yet been applied to the diagnosis and treatment following TKA. The objectives of gait analysis can be categorized into three distinct classes [5]: to describe the gait patterns of specific populations, to assess and classify the severity of functional impairment in specific populations, and to evaluate the effects of specific therapeutic interventions. It is commonly used to assess lower extremity pathologies, including chronic and acute knee disorders. Compared to patient self-report scoring methods, knee joint gait analysis offers a more objective and quantitative dynamic perspective for evaluating knee joint function and stability. Additionally, explaining postoperative functional recovery to patients based on kinematic data is more objective and comprehensible. It also provides more detailed and targeted rehabilitation training methods and precautions for patients who have not yet returned to normal ranges of motion, facilitating faster patient recovery, establishing a positive cycle, and increasing patient satisfaction.

Gait analysis is an examination method for studying walking patterns, aiming to reveal the key components and influencing factors of gait abnormalities through biomechanical and kinematic means, thereby guiding rehabilitation assessment and treatment. This contributes to clinical diagnosis, therapeutic efficacy assessment, and the study of underlying mechanisms. Gait analysis has also become a rehabilitation assessment method in the field of rehabilitation medicine, allowing the evaluation of rehabilitation effects and assisting physicians in developing better rehabilitation plans for patients. Gait analysis technology records the transitions of a series of typical postures contained in each gait cycle during walking, forming curves of gait kinematic parameters (such as the angle and displacement of the knee joint) over time. This can guide clinical decision-making in cases of gait dysfunction and is increasingly being used by clinicians to assess the function of the knee joint in various diseases [6]. The earliest motion capture researchers, led by the VICON company, developed a three-dimensional (3D) motion analysis system primarily based on multiple high-speed infrared cameras, which can directly record and compute the 3D spatial coordinates of markers, thereby obtaining the 3D coordinates of the test subject [7]. Three-dimensional motion capture systems can obtain relevant kinematic parameters, including degrees of freedom for angles and displacements [8], to comprehensively assess subtle changes in the knee joint during motion that are not easily discernible to the naked eye, allowing for a more scientific explanation of clinical phenomena. In summary, knee joint gait analysis systems are convenient, radiation-free, non-invasive, do not increase patient burden, and yield more objective results.

This trial was designed to assess the significance of gait kinematics in guiding postoperative rehabilitation under the hypothesis that gait kinematics would be helpful for the rapid recovery of patients after TKA. We utilized a 3D gait analysis instrument to conduct postoperative gait analysis on patients with TKA, comparing those who did not undergo gait analysis.

2. Materials and Methods

2.1. Case Data

This was an Institutional Review Board-approved retrospective cohort analysis (SPHFJP-K2022018-01). All patients who underwent cemented TKA for OA at the Second Affiliated Hospital of Fujian Traditional Chinese Medical University between December 2022 and July 2023 were considered for enrollment in the study. The healthy population data is provided by Shanghai Innomotion, Inc.

Inclusion criteria: 1) Patients with Kellgren-Lawrence grades III or IV varus knee osteoarthritis, with varus deformity < 15˚, flexion > 90˚, and flexion contracture < 10˚; 2) Candidates requiring unilateral TKA without contraindications; 3) Absence of tibial and femoral bone defects; 4) Ability to complete follow-up and gait analysis testing, with good compliance; 5) Voluntary participation in the study and provision of written informed consent.

Exclusion criteria include: 1) Knee varus or valgus deformity > 15˚; 2) Hip or ankle joint ankylosis/ankylosing deformities, or prior joint replacement surgery; 3) Known or suspected allergy to polyethylene, titanium, cobalt, chromium, or iron-containing materials; 4) Conditions preventing the ability to bear weight and/or stabilize the prosthesis due to illness; 5) Participation in other clinical trials of investigational drugs or devices within three months before the commencement of the study; 6) Inflammatory joint diseases and systemic multi-joint involvement (including the contralateral knee, bilateral hips); 7) Patients with peripheral soft tissue abnormalities and neurological disorders that might lead to erroneous gait analysis results.

2.2. Operation and Rehabilitation Procedure

A posterior-stabilized, without patellar surface replacement, fully cemented total knee prosthesis (Vanguard Premier; Zimmer Biomet, Warsaw, Indiana, USA) was used for all patients. The surgical approach is the medial parapatellar approach. A tourniquet was applied to the heel of the operated thigh, and the distal femur and proximal tibia were both cut perpendicular to the mechanical axis. The posterior condyle of the femur was cut parallel to the condyle axis. Install a trial mold to test the soft tissue balance in both straight and bent positions, and if necessary, use the "Pie Curesting" method to loosen the soft tissue. After the test is completed, rinse the wound with a pulse and then use bone cement to complete the prosthesis implanting. Place a negative pressure drainage tube and suture the incision. After the surgery, all patients received treatment such as infection prevention, preemptive analgesia, and thrombosis prevention, and immediately began a routine rehabilitation plan, including ice packs, continuous passive exercise (from full extension to flexion 110˚ - 120˚), and active and passive exercise under the guidance of a physical therapist. 24 hours after surgery, use a quadruped walker to assist with standing and walking, and the surgical limb can bear weight. If the patient is able to independently transition from a supine position to a sitting position, from a sitting position to a standing position, and walk safely with the assistance of a quadruped walker, and the passive flexion of the operated knee joint reaches 110 - 120˚, they can be discharged and returned home. Subsequently, 12 weeks after total knee replacement surgery, the patient will participate in a three-month outpatient rehabilitation program. The rehabilitation scope of this stage includes strengthening the quadriceps, restoring proprioception, gait training with appropriate weight-bearing in the lower limbs, and walking and climbing stairs without assistance. The intervention group conducted gait analysis at one month and three months after surgery, and then developed a personalized rehabilitation plan based on the analysis report results, starting two months of outpatient intensive rehabilitation training.

2.3. Gait Kinematic Analysis Protocol

A three-dimensional knee joint motion analysis system (Opti-Knee®, Shanghai Innomotion, Inc.) was employed for collecting gait kinematic parameters. A single researcher conducted the gait analysis. Subjects walked on a treadmill without assistance at their chosen speed for 3 minutes. High-speed cameras captured walking videos and gait data at a rate of 60 frames per second for a continuous duration of 15 seconds. Data collection was performed twice. Maximum and minimum values of each degree of freedom were collected; the difference between these two values constituted the range of motion.

2.4. Follow-Up Protocol

All follow-ups were conducted by two researchers who were not involved in the surgery or related clinical treatment. For all patients, standing weight-bearing knee anteroposterior and lateral and full-length lower limb X-rays were taken preoperatively. All patients underwent Hospital for Special Surgery score (HSS, 0 to 100 worst to best), Knee Society clinical score (KSS-Clinical, 0 to 100 worst to best), Knee Society function score (KSS-Function, 0 to 100 worst to best) assessments preoperatively (T0), and at 1 month (T1), 3 months (T2), and 6 months (T3) postoperatively. Knee anteroposterior and lateral X-rays were taken for all patients before discharge and at 3 months postoperatively; the intervention group underwent gait kinematic analysis at T1 and T2. Gait kinematic parameters included bilateral knees (angle parameters: flexion-extension, internal-external rotation, varus-valgus; displacement parameters: anterior-posterior, superior-inferior, medial-lateral), bilateral hips, and bilateral ankles (flexion-extension, internal-external rotation, varus-valgus). Clinical efficacy evaluation included HSS and KSS scores. Radiographic measurements included preoperative and postoperative hip-knee-ankle angle (HKA), lateral distal femoral angle (LDFA), and medial proximal tibial angle (MPTA).

2.5. Statistical Analyses

The data are presented as numbers, percentages, means, and standard deviations (SDs). The differences in the means of the primary outcome measures between the groups were determined using the Wilcoxon signed-rank test for nonnormally distributed data, an unpaired t test for normally distributed data. Categorical data were expressed as [n(%)]. Group differences were assessed through the chi-square tests or Fisher's exact test. In the comparison of measurement data of the same type of alignment in different follow-up timepoint, the repeated measure anova was employed. The data underwent analysis using statistical software (SPSS Inc. v20, IBM Corp., USA). A significance level of $\alpha = 0.05$ ($P < 0.05$) indicated statistical interpretation of differences.

3. Results

3.1. General Data

33 females and 17 males (68.3 ± 7.6 years) completed the preoperative and postoperative TKA assessments. All patients were followed up for 6 months. There were no significant differences between the two groups in terms of general data, preoperative imaging parameters, and functional score differences (P > 0.05) (Table 1).

Table 1. Comparison of the preoperative characteristics of the two groups.

Characteristics	Intervention Group (n = 25)	Control Group (n = 25)	P-value
Demographic			
Age (years)	68.46 ± 5.61	70.16 ± 6.81	0.34
Female	17 (68%)	16 (64%)	0.10
Male	8 (32%)	9 (36%)	0.12
BMI (Kg/m^2)	23.18 ± 1.68	24.13 ± 2.65	0.14
Range of motion			
Flexion Contracture	7.16 ± 6.85	6.26 ± 6.01	0.62
Flexion	118.43 ± 16.68	115.76 ± 14.89	0.55
Alignment			
LDFA	88.94 ± 4.57	89.19 ± 3.73	0.83
MPTA	84.94 ± 4.63	85.08 ± 4.09	0.91
HKA	9.12 ± 7.89	9.16 ± 7.78	0.99
Clinical measure scores			
KSS-Clinical	51.66 ± 14.02	49.76 ± 15.25	0.65
KSS-Function	54.99 ± 14.11	53.22 ± 10.88	0.62
HSS Scores	66.42 ± 9.42	65.94 ± 10.17	0.86

3.2. Gait Kinematic Scores

In the intervention group, the gait kinematic score of hip was lower than knee score (P < 0.05) at the first postoperative month (T1). No difference (P > 0.05) between knee and ankle at the first postoperative month (T1). After two months of individualized outpatient rehabilitation, there was a marked improvement in stride length and cadence at the third month (T2). The gait kinematic scores showed no difference (P > 0.05) in all joints (Table 2).

Table 2. Gait kinematics score of joints.

	Knee score	Hip score	Ankle score	P1-value	P2-value
T1	44.40 ± 1.35	41.05 ± 4.70	46.50 ± 7.30	0.00	0.16
T2	84.80 ± 10.43	86.20 ± 13.05	86.60 ± 10.09	0.68	0.54

P1: Hip score vs Knee score; P2: Ankle score vs Knee score.

3.3. Comparison of Postoperative Patient-Reported Outcome Measures (PROMs) between the Two Groups

Postoperative PROMs in two groups showed no difference between the two groups (P > 0.05) at one month postoperatively (T1). At three months postoperatively (T2), the PROMs of the intervention group were superior to the control group (P < 0.05). However, no significant differences were observed at the final follow-up (T3) between the two groups (P > 0.05) (Table 3).

Table 3. Comparison post-operative PROMs of the two groups.

	KSS-Clinical			KSS-Function			HSS		
	T1	T2	T3	T1	T2	T3	T1	T2	T3
Intervention Group	64.28 ± 12.31	74.99 ± 11.72	78.84 ± 9.53	61.23 ± 7.08	70.85 ± 10.18	73.20 ± 11.09	67.23 ± 6.76	76.27 ± 7.99	83.17 ± 5.31
Controlgroup	65.17 ± 11.19	67.50 ± 13.48	74.77 ± 11.51	60.32 ± 11.76	64.15 ± 11.28	71.03 ± 10.29	66.01 ± 5.49	70.37 ± 7.89	81.82 ± 7.60
P-value	0.79	0.04	0.18	0.74	0.03	0.48	0.49	0.01	0.47

3.4. Comparison of Lower Limb Alignment between the Two Groups

Postoperative X-rays of all patients showed no complications such as loosening or dislocation. There were no significant differences between the two groups in postoperative hip-knee-ankle angle (HKA), lateral distal femoral angle (LDFA), and medial proximal tibial angle (MPTA) (P > 0.05) (Table 4).

Table 4. Comparison of post-operative alignment of the two groups.

Alignment	Intervention Group	Control group	P-value
HKA	0.92 ± 1.14	1.35 ± 0.78	0.13
LDFA	90.03 ± 1.98	89.43 ± 1.36	0.22
MPTA	89.19 ± 2.03	89.63 ± 1.14	0.35

4. Discussion

This study collected preoperative and postoperative parameters at three stages of TKA patients, including one month postoperatively (standard rehabilitation plan), three months postoperatively (two months outpatient rehabilitation plan), and six months postoperatively (three months home-based rehabilitation plan). At one month postoperatively, patients exhibited shorter stride lengths and cadences, which may be associated with limited knee joint function (extension limitation, muscle weakness). The reduced gait kinematic scores could be related to insufficient strength in the muscles surrounding the joint. At three months postoperatively, patients showed significant improvements in stride length and cadence, and their gait kinematic scores also increased substantially.

Previous studies have already applied gait analysis in the assessment of TKA outcomes. Gait analysis revealed that the use of guiding technology can improve the maximum flexion angle of the knee joint during the swing phase after TKA, indicating that guiding technology contributes to the reconstruction of a more precise patellar trajectory and rotational alignment, preventing insufficient or excessive lateral displacement of the patella [9]. Compared with healthy elderly women, elderly women treated with TKA demonstrated reduced gait capability and muscle activity [10]. Gait analysis comparing pre- and post-TKA revealed that TKA significantly restricted coronal plane motion of the knee joint [11]. Post-TKA patients reported significant functional improvements and gradual reductions in gait abnormalities when compared to healthy populations, likely related to pain relief. However, at 15 weeks postoperatively, patients exhibited asymmetric stride length, which may reflect the influence of early postoperative tripod cane gait habits [12]. Only weak correlations were found between patient-reported outcome measures (PROMs) related to TKA and measurements obtained through gait analysis, such as speed, stride length, cadence, ground reaction forces, joint torques, and range of motion [13]. Gait analysis has also been utilized to compare the kinematic performance of different prosthesis designs [14] [15]. Additionally, gait analysis early post-TKA (14 days) has revealed correlations between gait abnormalities and surgical prognosis. However, to date, gait analysis has not been used to guide rehabilitation training.

Initial research concerning postoperative rehabilitation following TKA focused primarily on the quadriceps muscles. Studies suggest that optimizing quadriceps strength after TKA is crucial for achieving good functional outcomes [16], and the recovery of quadriceps size is also vital for post-TKA functional restoration [17]. Various rehabilitation protocols have also validated the importance of quadriceps strengthening [18]. Thus, early conventional rehabilitation plans concentrated solely on restoring the range of motion of the knee joint and quadriceps strength [19]. However, research has found that muscle weakness and functional limitations persist long after TKA under routine rehabilitation schemes. Compared with age-matched individuals without knee joint pathology, patients walk slower, find it more difficult to ascend and descend stairs, and struggle more with daily living activities [20]. These functional limitations are associated with the persistent muscle weakness observed in TKA patients [21], extending beyond the quadriceps. Studies indicate that hip strength is critically important for post-TKA outcomes [19]. This aligns with the findings of this current study, which identified that hip joint kinematic abnormalities were more common than knee joint issues at one month postoperatively. Hinman *et al.* [22] have anticipated that hip muscle weakness may persist following TKA. Piva *et al.* [19] also found that weakness in the hip abductor muscles has a greater impact on physical function than quadriceps weakness.

Considering that hip muscle strengthening can alleviate symptoms in patients with medial knee osteoarthritis [23], and that increases in vastus lateralis thickness and knee extensor strength can translate into enhanced physical function [24], this study developed a personalized rehabilitation plan for patients with kinematic abnormalities based on gait analysis results. The emphasis was placed on strengthening the muscles around the hip joint and lateral knee. Consequently, the intervention group patients started individualized functional rehabilitation plans when postoperative pain significantly subsided at four weeks. In the subsequent two months, as the intervention group patients implemented individualized outpatient rehabilitation treatment plans focused on improving hip and knee muscle strength, we observed continued improvement in functional scores. The scores at the third month postoperatively were superior in the intervention group compared to the control group, demonstrating a more rapid functional recovery.

This study has several limitations. First, the three-dimensional knee gait motion analysis system used in this study utilizes surface markers to mark the trajectory of knee joint movements. Compared with traditional VICON gait analysis, this system has shortcomings in evaluating the accuracy of axis rotation; second, we only collected gait data during T1 and T2 of walking on flat ground after surgery in this study, and did not collect gait data for other higher functional activities, preoperative and postoperative longer follow-up periods; and there is a lack of quantitative research on muscle group strength; in addition, the follow-up time is relatively short, so there may be measurement errors and selection biases. Further research is needed in the future to comprehensively understand the specific muscle weakness after total knee replacement surgery, in order to develop targeted rehabilitation plans for patients undergoing total knee replacement; more detailed research should be conducted on the muscle strength and beneficial effects on function after total knee replacement surgery to ensure that rehabilitation programs can address any serious persistent muscle strength deficiencies.

5. Conclusion

Gait kinematic analysis is helpful in evaluating the postoperative efficacy of TKA and can guide early and rapid recovery after TKA.

Funding

Research funds were provided by Fujian Medical Innovation Project Funding Program (2021CXA039) and Fujian Province Middle Aged Teacher Education Research Project (JAT210144).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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