SCIENTIFIC ARTICLE

Clinical Evaluation and Gait Characteristics before and after Total Knee Arthroplasty Based on a Portable Gait Analyzer

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Objective: To evaluate the effects of surgery and rehabilitation on patients undergoing total knee arthroplasty (TKA).

Methods: Twelve patients and 12 healthy controls were enrolled and their clinical scores evaluated by a doctor. Gait data, including walking velocity, stride length, single support time, foot fall and swing power, were collected using a portable gait analyzer from 12 patients before and 6 weeks and 6 months after surgery and from 12 healthy controls. The gait data and clinical scores at selected time points were compared and correlations between gait characteristics and clinical scores assessed.

Results: Clinical knee and knee function scores increased significantly from before surgery to 6 weeks to 6 months after surgery ($P < 0.001$). The only significant differences identified were for single support time on the diseased side between before surgery and 6 months after surgery ($P = 0.031$) and for foot fall with the diseased side between 6 weeks and 6 months after surgery ($P = 0.016$). Foot fall and speed of the healthy or diseased sides were significantly different in patients at all time points from those of the healthy subjects ($P < 0.05$). Single support time on the diseased side was significantly different 6 months after surgery ($P = 0.035$) in patients than in healthy controls. Single support time on the healthy side before surgery was significantly different from that of healthy controls ($P = 0.048$) and 6 weeks after surgery ($P = 0.042$). Stride lengths differed significantly between patients and healthy subjects before surgery (healthy side: $P = 0.007$; diseased side: $P = 0.008$) and 6 weeks after surgery (healthy side: $P = 0.001$; diseased side: $P = 0.001$), but were not different at 6 months after surgery (healthy side: $P = 0.088$; diseased side: $P = 0.077$). The only significant correlations identified were between single support time with the diseased side of patients and their knee ($r = 0.43$, $P = 0.032$) and knee function scores ($r = 0.493$, $P = 0.012$).

Conclusions: A portable gait analyzer appears to be suitable for evaluating the effects of TKA. Single support time on the diseased side may be a sensitive quantitative index for determining the effect of TKA and rehabilitation.

Key words: Clinical scores; Gait; Rehabilitation; Total knee arthroplasty

Introduction

Chronic joint disease in the lower limbs commonly occurs in older people, being a major cause of disability among patients over the age of 65 years. Because it can seriously

affect their quality of life, it is known as “the immortal cancer”¹. The increasing proportion of older persons in China has led to an increasing number of patients with lower limb joint disease².

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Artificial joints are used to replace damaged or non-functional human joints, thus restoring joint function, relieving pain, stabilizing the joint, correcting deformity and improving joint articulation³. Total knee arthroplasties (TKAs) have been increasingly performed in recent years, the success rate being greater than 95% at 10 years⁴. Surgical outcomes after TKA are commonly evaluated by a variety of clinical scores⁵, including the American Hospital for Special Surgery (HSS) knee score⁶ and American Knee Society (AKS) knee score⁶. However, these scores can be substantially influenced by patients' pain⁷. Additionally, although these scores are typically used to establish outcomes from TKA, such self-report measures have significant limitations. Specifically, self-report measures are dependent on patients' perceptions and patients may over- or underestimate actual functional ability⁸. In clinical practice, dependence on unadjusted scores for self-report measures could lead to erroneous conclusions concerning the ability of patients to move around post-arthroplasty⁹. Thus, there is currently a lack of effective quantitative methods for evaluating the overall surgical outcome and postoperative recovery of patients that can be used to guide subsequent rehabilitation exercises¹⁰.

Gait is a behavioral characteristic of human walking. Normal walking involves the coordinated movement of muscles and joints in the feet, ankles, knees, hips, trunk, neck, shoulders and arms. Disorder in any of these segments can affect the gait¹¹. Gait analysis has become an important clinical tool for evaluating treatment and rehabilitation. Gait analysis can identify whether patients with diseases of the nervous or motion system that can affect the ability to walk have an abnormal gait. Data from gait analysis can provide an objective reference for evaluating walking function and correcting abnormal gaits¹². In orthopaedics, gait analysis can be used as a reference for diagnosis and as a means of evaluation before and after treatment of orthopedic diseases¹³.

Previous studies analyzing gait to evaluate TKA have mostly been performed in specialized gait labs. Levinger *et al.* examined whether changes in foot posture and function occur after realignment of the knee during TKA¹⁴. These authors measures several gait variables using a 3-D motion analysis system (Vicon MX; Vicon Industries, Edgewood, NY, USA) with 10 cameras and two force plates (Kistler, Winterthur, Switzerland and AMTI, Watertown, MA, USA) at 1000 Hz. They found that TKA produced no change in static foot posture but did significantly alter hindfoot kinematics during gait. In that same year, they investigated whether biomechanical gait variables assessed before and at 4 months after surgery could predict an abnormal flexor moment pattern at 12 months after surgery¹⁵. Interventions aimed at improving active extension may need to be implemented as early as possible after surgery to restore to a normal gait pattern and their data may help in achieving that goal. In addition, Casatelli *et al.* compared the gaits of patients 6 months after unilateral total hip arthroplasty, TKA and total ankle arthroplasty with those of a group of

healthy controls by measuring spatiotemporal variables using the GaitRite system (GAITRite, CIR Systems, Clifton, NJ, USA)¹⁶. The gaits of TKA patients differed from those of controls, with slower walking velocities and reduced single-limb support in the involved limb. In another study, kinematic and kinetic changes during fast walking were investigated in patients undergoing endoprosthetic knee replacement. Eight patients underwent laboratory-based gait analysis (Vicon and Kistler) and the results were used to inform suggestions to those patients on how to increase their walking speed or redistribute their mechanical load onto muscles and other joints after knee reconstruction in order to prevent excessive stress on the lower limbs¹⁷.

These studies illustrate that gait analysis can be an important tool in orthopaedic research. However, most relevant research has been performed in specialized laboratories because the limitations of the hospital environment can make it difficult for to perform such testing. To address these issues, in the present study we used a portable gait analyzer (Intelligent Device for Energy Expenditure and Activity, IDEEA; MiniSun, Fresno, CA, USA) to collect gait data from patients before and 6 weeks and 6 months after TKA and compare them with the aim of assisting clinical evaluation of surgical and rehabilitation outcomes. Some researchers have already shown that IDEEA may be useful clinically^{18–20}. We aimed to evaluate whether patients' movement function improved after TKA by assessing changes in some gait parameters combined with clinical scores.

Materials and Methods

Subjects

Twelve patients with TKA and 12 healthy subjects were recruited from the Department of Orthopaedics, Beijing Jishuitan Hospital and Capital Medical University, Beijing, China. There were no significant differences in age, height, weight or body mass index between the patients and healthy subjects (Table 1). Informed consent was obtained from all subjects. The study protocol was approved by the Ethics Committee of Beijing Jishuitan Hospital.

Potential research participants were excluded from the study if they had a history of severe heart, kidney, Parkinson or Alzheimer disease. All patients were in a good mental state and were able to attend for the required follow-up and re-examinations. All the healthy subjects had normal lower limb joint function.

Gait Testing

The gait tests were performed using a portable multi-sensor gait analyzer (IDEEA3; MiniSun). This gait analyzer comprises one host device, two foot devices, and five limb mini-sensors. Gait data were collected using 3-D acceleration sensors pasted onto the thighs, ankles, feet and sternum. Real-time data were transmitted wirelessly to a host device worn at the waist (Fig. 1). The IDEEA is easy to wear and does not interfere with walking.

TABLE 1 Basic characteristics of study subjects

Index	Total knee arthroplasty patients	Healthy subjects	P value
Number of cases	12	12	–
Female/male	7/5	6/6	0.616
Age (mean $\pm$ SD, years)	65.33 $\pm$ 8.00	53.15 $\pm$ 6.68	0.388
Height (mean $\pm$ SD, m)	1.63 $\pm$ 7.55	1.64 $\pm$ 0.72	0.091
Body weight (mean $\pm$ SD, kg)	68.83 $\pm$ 12.60	68.92 $\pm$ 11.85	0.418
Body mass index (mean $\pm$ SD, kg/m ²)	26.59 $\pm$ 3.46	25.61 $\pm$ 2.65	0.238

Fig. 1 Photographs showing the portable device used to measure gait variables (the IDEEA, left), and the device sensor attachment points (right). The sensors are attached to the inferior point of the sternal angle, anterior midpoint of the thighs, lateral ankles, and soles between the fourth and fifth metatarsal bones. Once the device has been fitted and started, the subject can walk freely and data are automatically recorded by the device worn at the waist.

A runway with a lattice was prepared on a 20 m floor. After the IDEEA had been attached to the thighs, ankles, feet and sternum of the subjects and started, they were allowed to walk freely on the runway in order to adapt to the environment. During the test, the subjects walked at a normal pace back and forth (40 m) on the 20 m runway. When data acquisition had been completed, the data saved in the IDEEA were downloaded into a computer and analyzed using Gait-View 3.8 (Minisun).

Gait Variables

The following gait variables were assessed:

1. Walking velocity (m/s): The overall linear distance moved along the runway during walking per unit time was defined as the step or walking velocity.
2. Stride length (m): The distance from one heel striking the ground to the same heel striking the ground again during walking was defined as the stride length.

3. Single support time (ms): The single support time was defined as the time during which only one foot is in contact with the floor. This phase ends when the contralateral heel strikes the ground.
4. Foot fall (G; $1\text{ G} = 9.8\text{ m/s}^2$): The mean acceleration during a short acceleration descending process at the end of the swing phase in the longitudinal direction of the plantar sensor was defined as the foot fall. That is, when mid swing has finished, the gait cycle enters terminal swing and acceleration slows until the foot contacts the ground, which stops foot movement. Foot fall is a measure of the intensity of this deceleration process. Shank and foot forward movement depend heavily on thigh flexion and swift knee extension. The process of foot fall deceleration during the terminal swing is associated with impairment in patients with pathological gaits.
5. Swing power: The mean acceleration in the longitudinal direction of the foot at the end of the swing phase was defined as the swing power. That is, after finishing the initial swing, hip joint flexion causes knee, shank and foot forward acceleration. The intensity of this acceleration is defined as swing power (refers to muscle power herein). Swing power indicates the intensity of this process and is therefore strongly related to step length and velocity.

Data from specific time intervals (10 steps) were selected for each subject during stable walking.

Clinical Scores

In this study, AKS scores were used. These score have two major components: the knee score and the knee function score. The knee score includes perception of pain, range of motion, anteroposterior stability, medial-lateral stability, flexion contracture deformity, extension lag and valgus force line. The knee function score includes walking ability, ability to ascend and descend stairs and the use of supports.

Statistical Analysis

Statistical analysis was performed using SPSS 16.0 (SPSS, Chicago, IL, USA) and Excel 2010 (Microsoft, Redmond, WA, USA). All data are expressed as the mean $\pm$ standard deviation (SD). Changes over time in gait characteristics and clinical scores were evaluated by repeated measures ANOVA using Fisher's least significant difference *t* test for multiple comparisons. One-way ANOVA were used to test the significance of differences in gait variables between healthy subjects

and patients at the three time points. P values less than 0.05 were considered statistically significant.

Results

Clinical Scores Before and After Surgery

Clinical knee and knee function scores increased significantly from before surgery (knee score, 18.17 ± 6.44 ; knee function score, 17.50 ± 9.65) to 6 weeks (knee score, 51.67 ± 2.90 ; knee function score, 34.17 ± 9.96) to 6 months (knee score, 83.08 ± 2.47 ; knee function score, 60.00 ± 7.39) after surgery ($P < 0.001$).

Comparison of Gait Before and After Surgery

The assessed gait variables of foot fall, swing power, speed and stride length showed a tendency to increase from before surgery to 6 weeks and 6 months after surgery (Figs 2–6). The single support time on the healthy side fluctuated, whereas that of the diseased side appeared to increase.

However, statistical analysis with repeated measures design ANOVA showed that the differences were significant only for single support time on the diseased side between

before surgery and 6 months after surgery ($P = 0.031$) and foot fall on the diseased side between 6 weeks and 6 months after surgery ($P = 0.016$, Table 2).

Fig. 4 Comparison of foot fall at three time points on the patients' healthy and diseased sides and (healthy subjects: 4.77 G).

Fig. 2 Comparison of single support time at three time points on patients' healthy and diseased sides (healthy subjects: 403.06 ms).

Fig. 3 Comparison of speed at three time points on patients' healthy and diseased sides (healthy subjects: 1.273 m/s).

Fig. 5 Comparison of swing power at three time points on patients' healthy and diseased sides (healthy subjects: 0.73 G).

Fig. 6 Comparison of stride length at three time points on patients' healthy and diseased sides (healthy subjects: 1.35 m).

TABLE 2 *P* values for comparisons of gait variables between each pair of time points in patients (*n* =12) and healthy subjects (*n* =12) (healthy side/diseased side)

Time point	Single support time	Foot fall	Swing power	Speed	Stride length
Preoperation and 6 weeks after operation	0.820/0.358	0.437/0.351	0.508/0.307	0.383/0.426	0.373/0.360
Preoperation and 6 months after operation	0.235/0.031	0.891/0.075	0.875/0.532	0.383/0.426	0.373/0.360
Six weeks and 6 months after operation	0.191/0.198	0.587/0.016	0.473/0.767	0.231/0.296	0.163/0.181
Preoperation in patients and healthy subjects	0.048/0.992	<0.001/<0.001	0.217/0.216	0.003/0.002	0.007/0.008
Six weeks after operation and healthy subjects	0.042/0.372	<0.001/<0.001	0.079/0.884	0.001/0.001	0.001/0.001
Six months after operation and healthy subjects	0.583/0.035	<0.001/0.002	0.37/0.657	0.032/0.021	0.088/0.077

One-way ANOVA showed differences in the five gait variables between patients at the three time points and healthy subjects. There were no significant differences in the patients' swing power between any pair of time points for the healthy or diseased sides. In addition, there were no significant differences in swing power between the healthy sides of the patients at any time and the healthy subjects or between the diseased sides of the patients at any time and the healthy subjects ($P > 0.05$). In contrast, the foot fall and speed of both healthy and diseased sides of patients were significantly different from those of the healthy subjects at all time points ($P < 0.05$). The single support time on the patients' diseased side before surgery ($P = 0.992$) and 6 weeks after surgery ($P = 0.372$) did not differ from that of the healthy subjects; however, 6 months after surgery it was significantly different from that of the healthy controls ($P = 0.035$). The single support time on the healthy side was significantly different from that of healthy controls before surgery ($P = 0.048$) and 6 weeks after surgery ($P = 0.042$), but not 6 months after surgery ($P = 0.583$). The patients' stride lengths were significantly different from those of healthy subjects before surgery (healthy side, $P = 0.007$; diseased side, $P = 0.008$) and 6 weeks after surgery (healthy side, $P = 0.001$; diseased side, $P = 0.001$), but were not different 6 months after surgery (healthy side, $P = 0.088$; diseased side, $P = 0.077$).

Correlations between Gait Characteristics and Clinical Scores

The only significant correlations found were between patients' single support time with the diseased side and their

knee scores ($r = 0.43$, $P = 0.032$) and knee function scores ($r = 0.493$, $P = 0.012$; Table 3).

Discussion

Clinical Scores

Despite their limitations, clinical scores remain the current gold standard for assessing the outcomes of TKA in the clinic. The most commonly used knee scores are the Lysholm, AKS and HSS scores, International Knee Documentation Committee knee evaluation form, Western Ontario and McMaster Universities Osteoarthritis Index, American Academy of Orthopaedic Surgeons score, Knee Injury and Osteoarthritis Score and Cincinnati knee rating system. These methods have different focuses. The AKS score, a set of comprehensive scoring criteria proposed by the American Knee Society in 1989, comprehensively evaluates the overall function and morphology of the knee and accurately evaluates the condition of the joint itself⁶. AKS scores minimize bias during long-term follow-up and are considered one of the most effective knee scores for evaluating knee arthroplasty. In the present study, the AKS scores showed that knee function improved from before surgery to 6 weeks and 6 months after surgery.

Usefulness of IDEEA

The IDEEA is a portable gait analyzer that uses multiple 3-D accelerometers. The IDEEA is easy to wear and does not require wearing specialized or constrictive clothing. Without time or space limitations, the IDEEA can be worn for up to 1 week, which is why it is called the "gait holder"²¹. This

TABLE 3 Correlations between gait variables and clinical scores of 12 patients

Index	Healthy side		Diseased side	
	Knee score	Knee function score	Knee score	Knee function score
Single support time	-0.192	-0.18	0.43*	0.493*
Foot fall	-0.114	-0.26	0.275	0.257
Swing power	-0.005	-0.076	0.122	0.173
Speed	0.035	0.009	0.018	-0.048
Stride length	0.091	0.065	0.072	0.045

*, denotes significant difference ($P < 0.05$).

device provides an objective and quantitative method for gait analysis and enables the continuous monitoring of gait without influencing the patient's movement. In the present study, we used the IDEEA to measure gait variables in TKA patients before and after surgery and also assessed knee and knee function scores in the clinic. In addition, we made the same measurements on healthy subjects (control group). We assessed the recovery of patients' gaits with the aim of validating a quantitative means of clinically evaluating surgical and rehabilitation outcomes after arthroplasty.

Factors Influencing Effectiveness of Patients' Rehabilitation

Postoperative rehabilitation of the lower limb after arthroplasty is influenced by many factors, including the patient's general health and physical condition, whether or not rehabilitation exercises are strictly followed, duration of postoperative rehabilitation, type of prosthesis implanted, patient's weight and preoperative rehabilitation education²². In the present study, all patients followed the same rehabilitation program and had no surgical complications. Pre- and postoperative X-ray films were normal. According to gait measurements, three patients had decreased swing power and stride length 6 months after surgery. The surgical sites had not completely healed in these patients 6 weeks after surgery and their recovery was poor, which affected walking function and resulted in a reduction in some gait variables compared with before surgery.

Gait Characteristics

The TKA patients' assessed gait characteristics, including foot fall, swing power, speed and stride length, increased gradually on both the healthy and diseased sides from before surgery to 6 weeks and 6 months after surgery. In particular, foot fall on the diseased side was significantly greater 6 months after surgery than 6 weeks after surgery. Foot fall reflects pain and dysfunction during the terminal swing and initial contact. Neuromuscular dysfunction of the tibialis anterior and quadriceps femoris muscles and pain in the knee and ankle joints forces patients to put their feet down gently, reducing footfall and slowing cadency and velocity. Thus, an increase in foot fall is associated with increase in intensity of knee, shank and foot forward deceleration. Meanwhile, the greater the swing power, the faster the shank and foot accelerate. The changes we documented indicated that the patients' gaits improved over time after surgery.

However, the single support time on the patients' diseased sides increased steadily from before surgery to 6 weeks to 6 months after surgery; thus, the single support time was significantly greater 6 weeks after surgery than before surgery. However, the single support time on the healthy side increased 6 weeks after surgery and then decreased to preoperative levels 6 months after surgery. These changes suggest that the overall pain on the patients' diseased sides decreased and their movement function increased over time.

Compared with the gait characteristics of the, 6 months after surgery, the patients' foot fall was lower than that of healthy subjects on both sides, indicating that muscle strength around the knee had not fully recovered and that continuation of rehabilitation exercises was indicated. Simultaneously, changes in other variables indicated that the patients' walking function gradually approached normal after surgery, but had not reached healthy levels by the 6 month time point.

The 12 TKA patients had significantly greater single support time on the healthy than the diseased side before surgery because of lower limb pain. Therefore, these patients likely had significantly greater lower limb muscle strength on their healthy than on their diseased sides before surgery. After surgery, the single support time increased in 83% of patients, suggesting that the TKA increased the muscle strength of their lower limbs on the diseased side, but decreased it on the healthy side. Both before and after surgery, the single support time on the patients' healthy sides was longer than that in healthy subjects. However, the single support times on the diseased side were shorter than normal before surgery, but longer than normal after surgery, which is consistent with the findings of Casatelli *et al.*¹⁶. These results suggest that the patients used more muscle strength in their lower limbs after TKA when walking than did healthy subjects.

Comparison of data from each patient before and 6 months after surgery showed that, despite different variations 6 weeks after surgery, all patients had lower single support time, foot fall and swing power on the healthy side 6 months after surgery than before surgery, whereas stride length and walking velocity were both greater than before surgery. Single support time, foot fall, swing power, walking velocity and stride length were greater 6 months after surgery than before surgery on the diseased side. Studies by Casatelli *et al.* also showed greater walking velocity after than before surgery¹⁶. These results suggest that recovery is poor 6 weeks after surgery, but improves significantly with rehabilitation by 6 months after surgery.

Comparison of Clinical Scores and Gait Measurements for Evaluating the Effects of TKA

Currently, the main means of evaluating the effects of TKA procedures and rehabilitation are clinical scores acquired by asking the patients simple questions and making basic measurements, which is useful. However, these methods do accurately determine the patient's true condition because they are subjective and lack quantification. In the present study, we measured five patients' gait variables at different times with a portable gait analyzer. Of these, only the single support time on the patients' diseased sides correlated significantly with knee and knee function scores. These findings are in agreement with data reported by Senden *et al.*, who found no or only weak correlations between acceleration-based gait analysis variables and clinical scores²³. Our results suggest that single support time on patients' diseased sides may be a

more sensitive quantitative index for determining the effect of TKA procedures and rehabilitation.

Limitations of Our Study

The portable gait analyzer used in this study appears to be suitable for assessing outcomes after TKA and has the potential to overcome some of the limitations of stationary gait labs. This study's main limitations are its small size and large individual variation, which limited the statistical power in several of the gait variable comparisons. Thus, future studies should enroll more patients and further improve the experimental design. A combination of basic and clinical research

will provide more effective methods for scientifically assisting clinical diagnosis.

Conclusions

In conclusion, a portable gait analyzer appears to be suitable for evaluating the effects of TKA. Changes in kinetic (e.g., swing power) and spatiotemporal gait variables (e.g., single support time) after TKA indicated that patients' gaits improved, their values being closer to normal postoperatively than before surgery. The single support time on the diseased side of patients may be a sensitive quantitative index for determining the effects of TKA and rehabilitation.

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