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Article

Biomechanics-based optimization of knee joint rehabilitation technology and its integration with the health industry: Enhancing medical service efficiency and health economic value

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Abstract: Background: Knee osteoarthritis (KOA) is highly prevalent among the elderly population, with traditional treatments focusing primarily on medication or surgery, while precise rehabilitation and health economic evaluations remain insufficient. Biomechanics-oriented rehabilitation interventions may offer higher efficiency and safety. **Objective:** To explore the clinical efficacy, equipment performance, and cost-effectiveness of a novel rehabilitation training system based on biomechanical analysis for KOA patients and to verify the correlation between changes in joint torque and functional improvement. **Methods:** A total of 80 KOA patients were enrolled and randomly assigned in a 1:1 ratio into the intervention group and the control group, with 40 cases in each group. The intervention group utilized a novel rehabilitation training system incorporating biomechanical analysis, while the control group used conventional mechanical equipment. Three-dimensional gait parameters (e.g., peak joint angle, peak torque, loading rate) were measured at baseline, 6 weeks, and 12 weeks post-intervention. The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores and equipment performance indicators were assessed, while total treatment costs and cost-benefit ratios were calculated. The intervention effects were evaluated using independent sample t-tests, chi-square tests, and Pearson correlation analysis. **Results:** The intervention group showed significant improvements in peak joint angles, peak torque, and loading rates compared to baseline ($p < 0.05$), while soft tissue pressure did not increase significantly ($p > 0.05$). The novel equipment demonstrated significantly better performance in terms of angle and torque detection errors compared to conventional equipment ($p < 0.05$). The intervention group had lower total treatment costs and a superior cost-benefit ratio ($p < 0.01$), with no statistically significant difference in adverse event incidence ($p > 0.05$). Gait trajectory improvements were significant at multiple time points ($p < 0.05$), and clinical function (WOMAC score, walking distance) and healthcare efficiency also improved ($p < 0.05$). Changes in joint torque were strongly correlated with WOMAC score improvement ($r = 0.628$, $p < 0.001$). **Conclusion:** The biomechanics-driven rehabilitation training system significantly enhances clinical efficacy, equipment performance, and economic burden management, achieving precise rehabilitation and resource optimization, with demonstrable application value in the health industry.

Keywords: biomechanics; knee osteoarthritis; rehabilitation training; economic evaluation

1. Introduction

Knee osteoarthritis has a relatively high incidence among middle-aged and elderly populations, often leading to pain, joint functional impairment, and decreased quality of life [1]. Along with population aging and the increasing burden of chronic diseases, how to delay joint degeneration, reduce medical costs, and lower complication risks has gradually become an important issue. Previous studies have focused on pharmacological interventions and surgical treatments, and while findings continue to accumulate, there is still considerable potential for in-depth utilization of exercise biomechanics in the rehabilitation process [2,3]. The emergence of the Big Health industry has provided more integrated approaches for the prevention and rehabilitation of osteoarthritic conditions, while also highlighting the importance of precise and individualized interventions [4]. Clinically, there is widespread attention to joint cartilage wear and pain management, but a lack of systematic evaluation methods and feasible technical solutions for optimizing the mechanical environment makes early intervention or refined rehabilitation difficult to achieve [5]. Many conventional rehabilitation devices have issues such as insufficient adjustment accuracy and poor equipment stability, making it impossible to promptly monitor or dynamically regulate joint range of motion and load levels, leading to difficulties in ensuring training quality [6]. At present, there is still a lack of an overall solution that deeply integrates biomechanical assessment and rehabilitation technology, especially regarding how to improve rehabilitation efficiency through intelligent devices while also taking economic benefits into account, and no consensus has yet been reached on this topic [7]. Both clinical and industrial fields urgently require more effective research to verify the connection between optimized equipment and precise rehabilitation. This study targets patients with knee osteoarthritis and uses biomechanical analysis as its core, designing and evaluating a novel rehabilitation training system, and systematically verifying its effectiveness in improving joint function, enhancing the efficiency of healthcare service utilization, and reducing economic burdens. The study will focus on exploring the relationship between changes in mechanical indicators and improvements in clinical function, providing feasible evidence for the subsequent promotion of a biomechanical-oriented rehabilitation model within the Big Health industry. The highlight of this study lies in the combination of three forms of evidence—three-dimensional gait analysis, intelligent device performance evaluation, and cost-effectiveness analysis—to seek a balance between short-term therapeutic effects and long-term economic significance, thus laying a scientific foundation for large-scale application.

2. Materials and methods

2.1. Study design

This study is a single-center, prospective, randomized controlled trial aimed at investigating the impact of knee rehabilitation technology optimized through biomechanical analysis on patients' clinical functional recovery and efficiency of healthcare service utilization. The study was conducted at Beijing Jiaotong University from June 2022 to June 2024. All experimental procedures and clinical observations were carried out jointly by the Rehabilitation Department and the Orthopedics Department of the hospital, ensuring the same experimental environment and clinical operational processes. This study was officially approved by the hospital's Medical Ethics Committee, with approval number 2022-JTK-319.

2.2. Study participants

2.2.1. Inclusion and exclusion criteria

This study included outpatients diagnosed with knee osteoarthritis, aged between 50 and 70 years old. All patients had to meet the following conditions: a body mass index in the range of 18.5–30.0, no invasive joint surgery in the past 6 months, basic independent mobility, and voluntary signing of a written informed consent form. Exclusion criteria included severe cardiopulmonary insufficiency, neuromuscular diseases affecting gait or posture, mental or cognitive impairments, and inability to complete all follow-up procedures according to the study requirements.

2.2.2. Sample size and grouping method

Based on the standard deviation of the improvement in Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores observed in a preliminary pilot study and the set minimal clinically significant difference, G*Power software was used to determine that at least 34 cases per group would be needed to achieve statistical significance at the test level ($\alpha = 0.05$) and power ($1 - \beta = 0.80$). Considering a 15% dropout rate, 40 cases were enrolled in each group, totaling 80 cases. After enrolling patients who met the inclusion criteria, a dedicated statistician not involved in the study used a random number table for group assignment. Each patient received a unique number, and the group assignment was revealed in numerical order. Grouping was performed using a 1:1 parallel control approach, resulting in an intervention group and a control group.

2.3. Clinical intervention design

The intervention group completed 12 weeks of rehabilitation training on the novel knee joint rehabilitation training system, three times per week, each session lasting 60 min. This system achieves personalized biomechanical adjustment through an integrated motor drive module, angle sensors, and a real-time feedback unit. The motor drive module can output torque within the range of 0–60 Nm, with a torque adjustment accuracy of approximately ±0.5%, and it can automatically increase or decrease resistance according to training needs. The angle sensor has a resolution of about ±0.1° and collects joint position data in real time at a frequency of 100 Hz. The system control software performs real-time calculations of the angle and torque information based on predefined biomechanical target parameters; if the sensor feedback value exceeds or falls below the threshold range, it automatically corrects the output resistance and sends a prompt to the training interface, thereby maintaining the stability and safety of joint movement during training.

Before training, the system calculates the optimal resistance or assistance mode at different knee flexion and extension angles based on the patient's baseline range of motion, muscle strength tests, and three-dimensional gait parameters (obtained from previous assessments or built-in initial calibration). During training, the angle sensor continuously monitors the instantaneous range of motion and angle changes of the knee joint, while the motor drive module dynamically adjusts the output torque according to the predetermined biomechanical target curve: if it detects insufficient muscle strength within a certain range of knee joint angles, it automatically increases the assistance torque; if it detects that the joint range of motion and muscle strength meet the training goals, it gradually reduces assistance and appropriately increases resistance, prompting the patient to achieve more complete muscle engagement and joint control. The real-time feedback unit displays knee joint angle, torque variation curves, and timing information on the training interface, helping the therapist and patient observe the joint biomechanical status simultaneously and make fine adjustments, ensuring that the training intensity and rhythm match individual needs.

When the patient uses this system for passive, active-assisted, and active training modes, they can rely on a personalized support frame to maintain a stable knee joint axis, thereby reducing excessive twisting or swaying. The biomechanical analysis software of the system dynamically updates the training program according to indicators such as peak angle, peak torque, and stance phase duration before and after training so that subsequent training sessions gradually increase resistance or expand the range of motion. The control group used conventional mechanical rehabilitation equipment to manually adjust resistance and flexion-extension angles by means of a mechanical knob or lever, typically providing a knee joint range of motion of about 0°–90° but lacking real-time biomechanical monitoring and automatic torque output correction functions. During training, the therapist performed intermittent evaluations based on subjective pain and fatigue levels and manually adjusted the resistance, usually divided into 3–5 intensity levels, without the advantage of real-time biomechanical feedback. Both groups underwent rehabilitation training three times per week, each session lasting 60 min, for 12 weeks in total, and also received basic physical therapy measures (joint mobilization and conventional muscle strength training) to exclude factors other than equipment differences, thereby more objectively evaluating the effect of the biomechanically driven system on knee joint function and clinical outcomes.

2.4. Biomechanical parameter measurement and analysis methods

2.4.1. Measurement instruments and equipment

The experiment utilized a Vicon Nexus three-dimensional motion capture system (8 T160 infrared cameras, sampling frequency 120 Hz) and a Kistler 9287 force platform (sampling frequency 1200 Hz) to acquire gait kinematic and kinetic data. The force platform can record components of ground reaction forces and moment information. The biomechanics laboratory is equipped with a high-resolution camera, uniform lighting, and a fixed calibration setup. All instruments were calibrated by the same experimental engineer before measurement and verified using precise positioning of a calibration object.

2.4.2. Measurement procedures and data collection

Each subject underwent a 5-minute lower limb warm-up before the formal test to ensure a relaxed state of the lower limb muscles. Reflective markers were attached by the researchers to the bilateral anterior superior iliac spines, lateral femoral condyles, fibular heads, medial malleoli, and lateral malleoli. The entire experiment was conducted in a stable environment at 24 ± 2 °C, with humidity at 50%–60%.

(1) Static calibration: The subject maintained a standing posture on the force platform for 5 s. This process was used to calibrate the initial positions of each marker.

(2) Dynamic measurement: The subject walked at a comfortable speed along a

10-meter-long level walkway, crossing the force platform positioned in the middle. Each subject completed 3 valid walking tests, with an interval of about 2 min [8]. During data collection, marker trajectories were observed in real time. If signal loss or reflective interference occurred, recalibration was performed and additional tests were carried out.

Vicon Nexus software synchronously recorded the raw data from the cameras and the force platform and stored them on an encrypted server. After the test, the subject removed the markers and left the laboratory.

2.4.3. Data processing and analysis

The collected three-dimensional coordinate data and ground reaction force information were processed using a dedicated algorithm written in MATLAB 2022a. The gait cycle was defined from the moment the foot first contacted the force platform to the moment the same foot contacted the force platform again. After removing incomplete gait cycles and obvious outliers, peak values of joint angles and joint moments, loading rate, duration of the lower limb support phase, and soft tissue loading pressure were extracted. The average of the 3 valid tests per subject was used in the statistical analysis. Two independent researchers performed the analysis, cross-checking results before outputting them to the final database.

2.5. Health technology performance and accuracy evaluation methods

2.5.1. Pre- and post-improvement device comparison

The intervention group was equipped with a novel knee rehabilitation training system produced after optimization based on previous biomechanical data, consisting of a main control unit, an angle sensing module, a motor-driven device, and a personalized support frame. The control group was equipped with conventional mechanical knee rehabilitation equipment. Both types of equipment underwent uniform performance testing before the start of the study to confirm that they met the factory specifications and technical indicators provided by the manufacturer.

2.5.2. Performance testing environment and operating procedures

All equipment testing was carried out under the same environmental conditions (temperature 24 ± 2 ℃, relative humidity 50%–60%), and all equipment was uniformly calibrated according to the manufacturer’s instructions prior to testing. The equipment in the intervention group relied on a programmable motor to output multiple levels of resistance and auxiliary torque, while the control group performed training motions through knob-type mechanical resistance. In order to quantify angle detection error, a high-precision mechanical goniometer (accuracy ± 0.1°) was used to perform calibration at five incrementally increasing angles within the 0°–90° range; after the equipment automatically positioned each angle, the difference between the system reading and the goniometer’s measured value was recorded, and the absolute deviation was calculated. When measuring output torque error, a torque sensor (measurement range covering the training resistance range, accuracy better than ± 0.5%) certified by national metrology authorities was used to record the equipment’s set target torque and the measured torque, and the difference between the two was calculated and expressed as an absolute or relative error. Continuous operation stability was set for a duration of 20 min, with the equipment placed at a medium resistance level to operate continuously without human intervention. The software collected output torque every minute and calculated the maximum fluctuation amplitude and coefficient of variation. All data were measured three times and averaged. During the testing process, the device technician and the data recorder cooperated to avoid bias caused by subjective operations, and finally, the test results were summarized and statistically analyzed by an independent inspector.

2.5.3. Collection and comparison of key indicators

After the performance tests, the precision, output stability, and failure rate of the equipment in both the intervention group and the control group were recorded in a performance evaluation form. Finally, these indicators were statistically compared by an independent inspector to assess the level of technical support each type of equipment provided for knee rehabilitation training.

2.6. Clinical efficacy and service utilization efficiency evaluation methods

2.6.1. Evaluation indicators and data collection

The primary efficacy indicator is the WOMAC score [10]. This scale consists of 24 items, divided into pain (5 items), stiffness (2 items), and daily activity function (17 items), with a total score range of 0–96. A higher score indicates more severe symptoms. Each item is scored from 0 to 4, and the pain level, joint stiffness, and functional impairment are summed accordingly.

Secondary indicators include the 6-minute walk test performance [11] (measured in meters) and the maximum flexion and extension angle of the knee joint (measured in degrees). Subjects wore the same model of pedometer for the 6-minute walk test, with consistent timing and start/end point setup. The maximum knee flexion and extension angle was measured by the same rehabilitation therapist using a goniometer.

Service utilization efficiency was assessed by average single-visit duration, waiting time for rehabilitation training, total treatment costs, and incidence of adverse events. Researchers obtained time and cost data from the medical record system. Adverse events include secondary injury, acute complications, and withdrawal from training midway.

2.6.2. Data collection process and follow-up

All clinical evaluation indicators were measured and recorded at baseline, Week 6, Week 12, and Week 24. The measurement at Week 24 was only used as data for subsequent long-term observation and not included in the main statistical analysis. Before the end of the study, an independent research assistant checked the database for logical or input errors, and after excluding these errors, compiled the final analysis dataset. If any adverse events occurred during the intervention, the research team immediately evaluated the risk and recorded the event type and severity.

2.7. Data statistics and analysis

Paper forms and electronic spreadsheets were stored separately, and dual data entry was conducted. The entries were then compared by the system to ensure accuracy. If the missing data rate was below 5%, multiple imputation was used; if it exceeded 5%, the related records were excluded, and the reason was noted. Measured data were reported as mean and standard deviation or median and interquartile range, while count data were reported as frequency and percentage. For variables measured repeatedly at multiple time points (baseline, Week 6, Week 12, etc.), repeated-measures analysis of variance or mixed linear models were used to test the group × time interaction effect [12]. If the assumptions of normality or homogeneity of variance were not met, corresponding non-parametric methods and corrections were applied. Other continuous variables following a normal distribution were compared between groups using independent-samples t-tests. Count data were expressed as the number of cases and percentages, and between-group comparisons were conducted using the chi-square test or Fisher's exact test. The correlation between the change in joint torque and the improvement in WOMAC scores was analyzed by Pearson correlation, and a linear regression line was plotted. All tests were two-sided, with a significance level set at 0.05.

3. Results

3.1. Baseline characteristics of the study subjects

Baseline comparisons were performed using independent-samples t-tests or chi-square tests. Results showed no statistically significant differences in age, sex, body mass index, and baseline WOMAC scores between the two groups ($p > 0.05$), indicating balanced grouping. No further covariate adjustment was needed, meeting RCT requirements (**Table 1**).

Table 1. Comparison of baseline demographic and clinical characteristics between the two groups of subjects.

Variable	Intervention group (n = 40)	Control group (n = 40)	Statistic	p value
Age (years)	62.35 ± 5.84	61.80 ± 5.96	$t = 0.443$	0.659
Sex (male/female)	18 (45.00%)/22 (55.00%)	15 (37.50%)/25 (62.50%)	$\chi^2 = 0.475$	0.491
BMI (kg/m^2)	26.78 ± 2.68	27.06 ± 2.71	$t = 0.603$	0.548
Baseline WOMAC total score (0–96)	50.72 ± 5.43	51.29 ± 5.66	$t = 0.394$	0.695

3.2. Biomechanical parameter analysis results

In the intervention group, the peak joint angle, peak joint torque, and loading rate all showed statistically significant improvements at 12 weeks compared to baseline (t-test, $p < 0.05$), whereas changes were smaller in the control group, and soft tissue pressure at 12 weeks did not show a notable difference (t-test, $p > 0.05$). These findings indicate that the post-intervention improvements were more pronounced in the intervention group (**Table 2**). At baseline, there were no significant differences in knee joint angle trajectories between the two groups for most points in the gait cycle (t-test, $p > 0.05$). After 12 weeks of intervention, the intervention group showed a significant increase in angle at multiple time points (t-test, $p < 0.05$), demonstrating a more pronounced improvement in joint range of motion (**Figure 1**).

Table 2. Changes in key biomechanical parameters before and after intervention ($\bar{X} \pm$ SD).

Variable		Intervention group (*n* = 40)	Control group (*n* = 40)	Statistic (*t*)	*p* value
Peak joint angle (°)	Baseline	46.28 ± 4.59	45.84 ± 4.51	0.359	0.720
	12 weeks	49.53 ± 4.92	47.12 ± 4.73	2.427	0.018
Peak joint torque (Nm)	Baseline	66.34 ± 8.94	65.88 ± 8.72	0.204	0.839
	12 weeks	72.14 ± 9.14	68.56 ± 8.88	2.048	0.044
Loading rate (BW/s)	Baseline	14.26 ± 1.62	14.49 ± 1.58	0.571	0.570
	12 weeks	13.02 ± 1.47	13.81 ± 1.52	2.145	0.035
Soft tissue pressure (kPa)	Baseline	28.64 ± 3.21	28.49 ± 3.18	0.210	0.834
	12 weeks	26.97 ± 3.04	27.82 ± 3.12	1.587	0.117

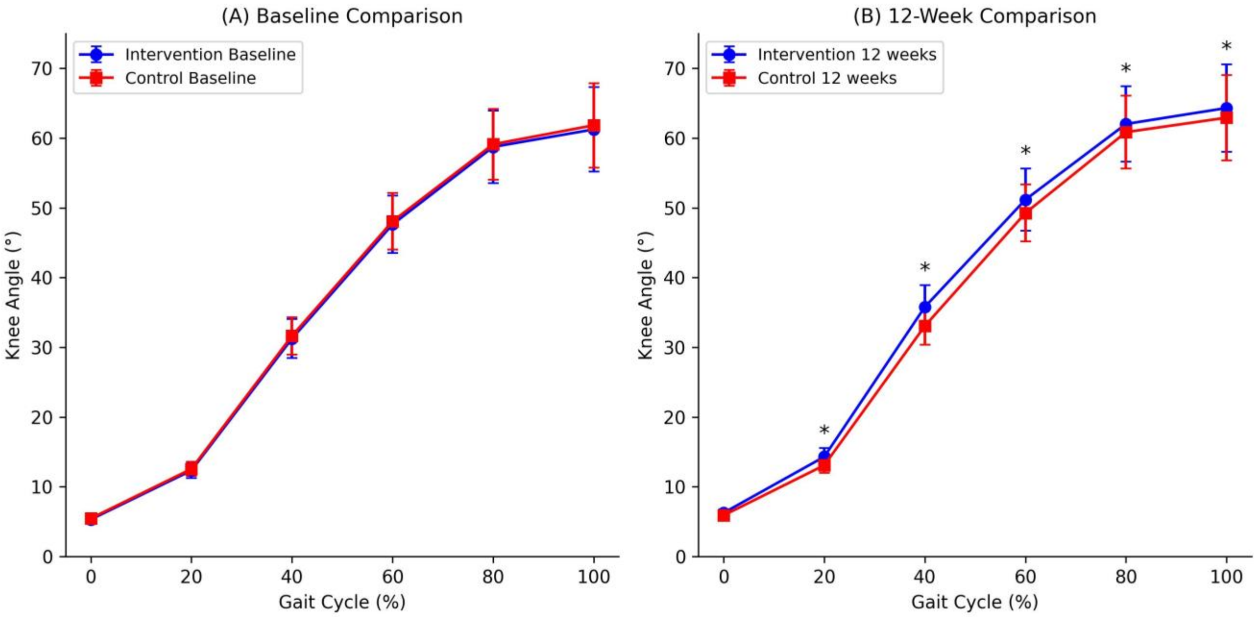

Figure 1. Comparison of lower limb joint motion trajectories in three-dimensional gait analysis.
Between-group comparisons were performed using the *t*-test, and * indicates $P < 0.05$.

3.3. Equipment performance evaluation results

The results show that, according to the independent-samples t-test, the novel rehabilitation training system is significantly superior to conventional equipment in terms of angle detection error, output torque error, continuous operation stability coefficient, and mean time between failures ($p < 0.05$) (**Table 3**).

Table 3. Performance test results of the novel rehabilitation training system vs. conventional equipment ($\bar{X} \pm$ SD).

Performance indicator	Novel rehabilitation training system	Conventional rehabilitation equipment	Statistic (*t*)	*p* value
Angle detection error (°)	1.48 ± 0.17	2.03 ± 0.21	2.945	0.004
Output torque error (Nm)	0.58 ± 0.07	0.91 ± 0.09	3.427	0.001
Continuous operation stability coefficient (%)	2.67 ± 0.31	3.24 ± 0.36	2.221	0.03
Mean time between failures (hours)	143.28 ± 11.25	122.69 ± 9.82	2.938	0.005

3.4. Clinical efficacy and service utilization efficiency

At weeks 6 and 12, the intervention group showed significantly better results than the control group in WOMAC score (**Figure 2A**), 6-minute walking distance (**Figure 2B**), maximum knee flexion and extension angle (**Figure 2C**), single-visit duration (**Figure 2D**), and waiting time (**Figure 2E**) (t-test, $P < 0.05$). The group × time interaction effect was also statistically significant (F-test, $P < 0.01$), indicating a more pronounced improvement trend after intervention. The total treatment cost in the intervention group was significantly lower than in the control group, and the cost-effectiveness ratio was also markedly better (t-test, $p < 0.01$). There was no statistically significant difference in adverse events or readmission rate (χ^2 test, $p > 0.05$). This demonstrates that the intervention is more advantageous in balancing economic burden and benefits (**Table 4**).

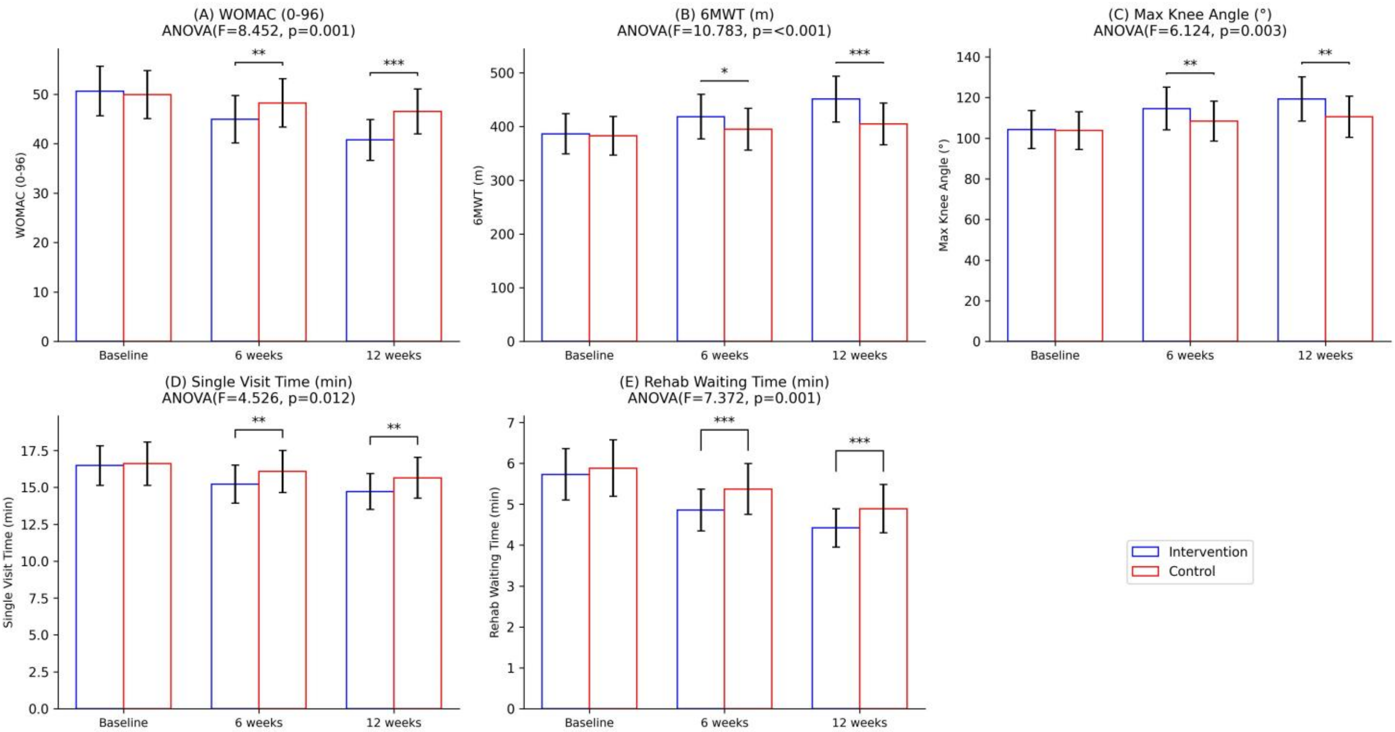

Figure 2. Clinical efficacy and service utilization efficiency indicators; **(A)** WOMAC score; **(B)** 6-minute walking distance; **(C)** maximum knee flexion and extension angle; **(D)** average single-visit duration; **(E)** rehabilitation waiting time.

Between-group comparisons were performed using the t-test, and repeated-measures ANOVA was used for the group × time interaction. * indicates $P < 0.05$, ** indicates $P < 0.01$, *** indicates $P < 0.0001$.

Table 4. Medical costs and cost-benefit analysis results.

Variable	**Intervention group (n = 40)**	**Control group (n = 40)**	**Statistic**	***p* value**
Total treatment cost (RMB)	11,938.72 ± 954.31	13,164.58 ± 1061.09	$t = 3.027$	0.003
Adverse event incidence rate (%)	9.85 (4/40)	14.76 (6/40)	$\chi^2 = 0.596$	0.44
Readmission rate (%)	3.70 (1/40)	10.26 (4/40)	$\chi^2 = 1.358$	0.244
Cost-effectiveness ratio (CER, RMB/point)	328.47 ± 31.28	399.56 ± 36.42	$t = 3.871$	< 0.001

Note: Taking improvement in WOMAC score as the primary efficacy indicator, the cost-effectiveness ratio represents "the average cost required to improve the WOMAC score by 1 point (CER = total treatment cost/efficacy increment)".

3.5. Correlation analysis between biomechanical indicators and WOMAC improvement

In the scatter plots, the change in peak torque in the intervention group is significantly correlated with WOMAC improvement ($r = 0.628$, $p < 0.001$, $R^2 = 0.394$), whereas the correlation is weaker in the control group ($r = 0.355$, $p = 0.029$, $R^2 = 0.126$). The two subplots display the scatter points and regression lines, highlighting the stronger correlation in the intervention group. This further indicates a differentiated correlation between changes in joint torque and functional improvement (**Figure 3**).

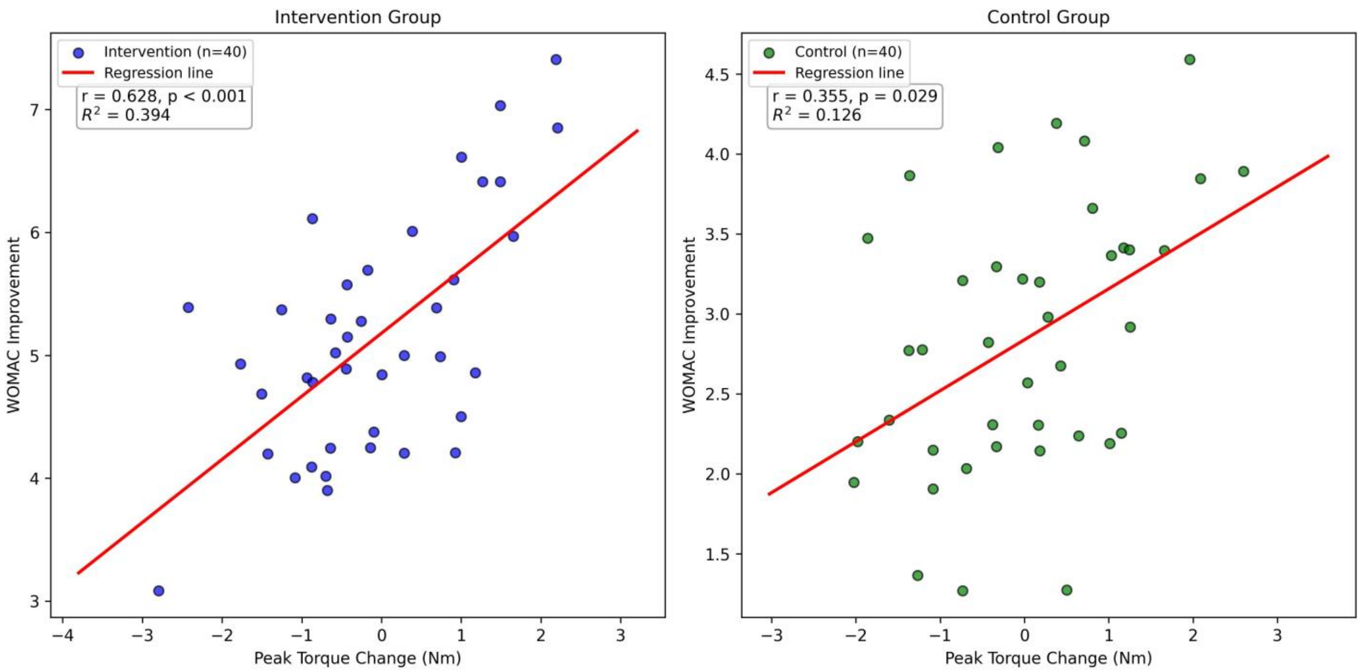

Figure 3. Correlation analysis between biomechanical indicator improvement and WOMAC improvement.

4. Discussion

In the intervention group, peak joint angle, peak torque, and loading rate increased significantly, and no additional burden on soft tissue pressure was observed, indicating that by regulating mechanical load and the range of angular motion, it is possible to enhance function while protecting the joint structure. Three-dimensional gait analysis revealed that the motion trajectories of the swing phase and stance phase became more physiologically aligned, suggesting that a biomechanical intervention approach can more precisely correct abnormal knee joint dynamics, thereby alleviating clinical symptoms and improving daily activity capacity [13]. Considering the disease progression of knee osteoarthritis, this intervention model targeting the mechanical environment not only promotes pain relief and improves range of motion in the short term but also provides a potential strategy for slowing cartilage degeneration and preventing joint deformities [14]. The findings are consistent with existing literature indicating that "mechanical optimization can slow joint wear", and further highlight the value of biomechanical assessment in early monitoring and individualized treatment planning for degenerative joint disease [15]. By closely integrating biomechanical assessment tools with the rehabilitation training system, clinicians gain a more objective method for process evaluation so that the intervention's effectiveness is no longer limited to patients' subjective perceptions but can be validated using quantitative indicators to determine whether the established goals have been met. This complete chain from assessment to intervention underscores the importance of precision rehabilitation and also provides a viable approach for further refining knee joint disease management in the Big Health industry. The study shows that leveraging rehabilitation technology improved through biomechanical assessments can yield multiple benefits, including enhanced healthcare quality and reduced burden on individuals and society. Further promotion of such technologies will help expand the depth and breadth of degenerative joint disease prevention and treatment at both clinical and industrial levels.

The new rehabilitation training system's performance advantages in angle detection, output torque, and operational stability provide higher precision and safety during clinical rehabilitation, while also reducing reliance on healthcare personnel and patients [16]. The study results confirm that combining biomechanical principles with real-time feedback technology can make the equipment more flexible when correcting movements and distributing loads. For patients, lower angle and torque deviations help reduce additional stress on joint structures, preventing potential secondary injuries caused by cumulative deviations. For healthcare institutions, long-term equipment stability and a longer mean time between failures not only mean more controllable maintenance costs but also help maintain training quality even under busy department conditions or high bed turnover rates. From an industry perspective, new intelligent rehabilitation equipment leveraging biomechanical concepts and information-based methods can be rapidly iterated and broaden its application scenarios, offering wider market potential within the Big Health industry [17]. Precision and high integration of medical equipment also attract capital and research and development investment, thus creating a virtuous cycle in large-scale production and service optimization, ultimately enhancing overall healthcare service efficiency [18]. The study results demonstrate the dual promotion effect of technological innovation on rehabilitation quality and industry development, aligning with the core argument of this research by indicating that the deep integration of biomechanics and health technology can not only improve rehabilitation outcomes but also drive the overall upgrade and sustainable development of the Big Health industry.

The advantages of the intervention group in clinical indicators and time efficiency indicate that an intervention strategy based on biomechanical principles helps accelerate rehabilitation and conserve resources. The improvement in WOMAC scores and walking ability reflects pain relief and functional enhancement, and it also directly impacts patients' independence in daily activities and quality of life. For patients with knee osteoarthritis, the degree of pain and joint function often determines their accessibility and safety in walking, climbing stairs, or prolonged standing. Improving these core indicators not only reduces the psychological burden caused by pain but also allows patients to regain more social functions and family roles. Clinically, it has been observed that, at later follow-up visits, the intervention group finds it easier to return to light physical work or maintain higher frequencies of outdoor activities, further emphasizing the significance of pain relief and functional recovery in everyday life. Meanwhile, the shortened visit and waiting times reflect process optimization and enhanced departmental efficiency. Lower treatment costs and a better cost-effectiveness ratio indicate that precision technology can balance high-quality healthcare with reasonable expenditures [19]. In this study, the cost savings in the intervention group mainly come from two aspects: first, real-time mechanical monitoring and automatic adjustment reduce the frequency of manual interventions and repetitive operations; second, training outcomes are more precise and efficient, enabling the expected rehabilitation goals to be achieved in the same or even a shorter treatment course, thereby shortening hospitalization or outpatient periods and saving on related consumables and venue costs. It should be noted that the new equipment may face a higher one-time investment in early procurement and installation, and equipment maintenance and technical upgrades can also incur additional costs; meanwhile, the training requirements for medical staff are higher than those of conventional equipment, necessitating more systematic study of biomechanics and system operation. However, from the perspective of long-term use, fewer malfunctions, lower manpower demands, and faster rehabilitation processes can offset and surpass these early investments in total cost, underscoring this system's advantages in overall economic feasibility.

The study found no significant differences in adverse events and readmission rates in the intervention group, suggesting that this model does not increase safety risks while enhancing efficiency. From the perspective of the Big Health industry, such an integrated rehabilitation program can balance efficacy and economic burden, achieving better outcomes in a shorter time with lower costs, thus creating a win-win situation for hospitals and patients. Healthcare administrators can incorporate this into routine pathways to optimize resource allocation, and promoting this strategy in primary-level institutions may help reduce regional healthcare disparities [20]. The superior performance of the intervention group indicates that clinical practice should not rely solely on anatomy or medication; instead, it can combine biomechanics with modern technology to improve treatment quality more precisely, in line with Big Health's comprehensive, multi-level intervention philosophy, thereby forming a positive synergy at both hospital and industry levels. Balancing rehabilitation efficiency and economic benefits also helps attract social capital and research investment, driving technological upgrades and promoting transformation in healthcare service models [21]. Studies have shown that simply relying on traditional physiotherapy alone cannot achieve the same level of cost control and clinical improvement. In contrast, integrating biomechanical assessment not only optimizes physiological indicators but also provides evidence-based support for the promotion of health technologies.

The stronger correlation between the change in joint torque in the intervention group and the improvement in WOMAC scores indicates that under biomechanical optimization, fluctuations in mechanical parameters more accurately reflect the progress of functional recovery. This predictive value allows physicians to adjust rehabilitation strategies based on mechanical indicators, helping patients achieve their goals more quickly. Although the control group also showed a positive correlation, the value was weaker, indicating that conventional equipment fails to provide precise biomechanical feedback, thereby limiting rehabilitation effectiveness. This difference corroborates the study's core viewpoint that deeply integrating biomechanical principles can overcome crude interventions, realize precision medicine, and meet the needs of different patients [22]. Future research may incorporate additional data collection methods, combining imaging and physiological/biochemical indicators to explore the synergistic effects of multidimensional information. With the development of smart healthcare, data platforms and AI algorithms can integrate multisource data to further investigate the potential mechanisms between joint torque and clinical outcomes, constructing personalized rehabilitation programs. Long-term management can include quality of life, social participation, and mental health indicators, fostering the convergence of medicine and industry. The study suggests that the positive correlation between biomechanical improvement and functional improvement can be validated in multicenter or even large-scale populations. If community rehabilitation and out-of-hospital services can be integrated, biomechanical-driven rehabilitation programs may provide tiered diagnosis and treatment with individualized guidance, reinforcing public health safeguards and expanding new ideas in the Big Health industry.

5. Conclusion

This study adopted a combination of biomechanical principles and an intelligent rehabilitation system to deliver precision interventions for patients with knee osteoarthritis. The results showed that the intervention group outperformed the control group in biomechanical indicators, clinical efficacy, service efficiency, and health economics and was more closely correlated with improvements in joint function. This indicates that optimized training centered on biomechanical assessment can effectively enhance rehabilitation quality, reduce medical costs, and achieve a win-win scenario for precision medicine and Big Health industry development. It is recommended that subsequent research include multicenter, large-sample validation, along with long-term follow-up and multidimensional indicators, to provide more robust evidence for improving the biomechanical-led rehabilitation model and its industrialization pathway. Connecting this approach to community rehabilitation systems can realize tiered diagnosis and treatment with personalized programs, benefiting a broader population and contributing to the upgrade of health services.

Conflict of interest: The authors declare no conflict of interest.

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