Research on the Application Innovation of Digital Virtual Simulation Technology in Vocational Education Practical Teaching and the Improvement of Students' Practical Operation Ability

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ABSTRACT Practical teaching in vocational education faces major constraints, including limited training venues, high-risk operating environments, expensive consumables, and insufficient personalized guidance. To address these problems, this paper systematically explores the innovative application of digital virtual simulation technology and its mechanism for improving students' practical operation ability. Based on questionnaire surveys, experiments, and case studies, data from 12 vocational colleges in six provinces are used to analyze current application conditions and key problems. Four training modes are designed, namely contextualized immersive training, modular stepped training, personalized adaptive training, and inter-school collaborative simulation training. Three technical paths are further proposed: digital twin integration, AI-enabled evaluation, and micro-simulation-based fragmented learning. Empirical tests in majors such as mechatronics and nursing verify that the proposed mode significantly improves practical operation ability. The results show that virtual simulation technology can reduce long-term comprehensive training costs by more than 80% in typical high-risk or consumable-intensive scenarios and shorten the training cycle by 50%, providing a feasible technical solution for practical teaching reform in vocational education.

INDEX TERMS virtual simulation technology, vocational education, practical teaching, digital twin, simulation training

I. INTRODUCTION

A. RESEARCH BACKGROUND

VOCATIONAL education serves as the core carrier for cultivating technical and skilled talents within the industry, where practical teaching in modern spinning, weaving, and digital fashion design constitutes its essential feature and core link. This hands-on approach ensures that students master the technical complexities of advanced machinery and innovative production, which are vital for meeting the evolving demands of the global market. However, current vocational education practical teaching in China still faces multiple structural dilemmas. Firstly, the existing on-campus internship venues of many vocational colleges cannot meet the needs of practical teaching, resulting in a significant gap in practical training venues and equipment resources [1, 2]; secondly, due to certain constraints, practical training courses in high-risk industries such as chemical engineering are difficult to carry out, such as dangerous experiments involving highly toxic reagents or toxic gas emissions in organic chemistry experiments [3]; thirdly, there is a large investment in consumables and high later maintenance costs, such as bars and tools for mechanical processing, and wires and components for electrical control [4]; fourthly, insufficient personalized guidance leads to uneven mastery of skills [5].

The Vocational Education Program Catalog (2024) clearly proposes to "deepen integration with vocational education", and the construction standards of the "Double High-Level Program" list virtual simulation training bases as core indicators [6]. Digital transformation not only requires vocational education to innovate teaching methods but also emphasizes the construction of a new practical teaching ecology of "combination of virtual and reality, integration of online and offline", which poses a severe challenge to the traditional training mode dominated by "master-apprentice teaching".

Digital virtual simulation technology can create a simulated environment of the real world, providing comprehensive sensory cognition and practice, with the advantages of high-fidelity restoration, risk-free training, and full-process traceability, which is highly consistent with the needs of vocational education practical teaching [7, 8].

Based on the above background, this study aims to explore the systematic application and teaching mode construction of digital virtual simulation technology in vocational education, focusing on simulating complex processes like automated spinning and smart garment manufacturing. The research evaluates its effectiveness in improving students' dimensions such as machinery operations, comprehensive application of fabric engineering, problem-solving in quality control, and design innovation capabilities.

B. RESEARCH SIGNIFICANCE

(1) Enrich the theoretical system of digital teaching in vocational education, reveal the internal logic of the in-depth integration of virtual simulation technology and practical teaching, improve the theoretical mechanism of technology empowering the improvement of practical operation ability, and provide theoretical support for research in related fields.

(2) Provide feasible innovative solutions for vocational colleges to solve dilemmas such as shortage of practical training resources and high costs, optimize the training path of students' practical operation ability, and improve the quality of talent training and employment competitiveness.

(3) Provide practical references for education administrative departments to formulate policies and technical R&D institutions to develop resources.

1) Review of Domestic and Foreign Research Status

2) Research Status of Virtual Simulation Technology Application in Vocational Education

Domestic research focuses on the expansion of technical application scenarios and local model innovation. For example, Wang et al. applied virtual simulation technology in oral practice experiments [9]; Cai et al. developed a milling processing virtual simulation system based on zSpace through augmented reality, virtual reality and other technologies, and applied it in milling processing practical teaching [10]. Technology application is mainly based on VR/AR and simulation software, and the integrated application of new technologies such as digital twin and AI empowerment is still in its infancy.

Foreign countries have invested virtual simulation technology in the field of education earlier, and it has been widely used in the educational field of different majors [11, 12]. However, foreign research is mostly based on their local education systems, and its adaptability to China's vocational education needs to be verified.

3) Research on the Improvement of Vocational College Students' Practical Operation Ability

Existing research has clarified the multi-dimensional composition of practical operation ability, including three levels: basic skills, professional ability, and high-level ability. Its improvement paths focus on traditional modes such as school-enterprise cooperation and project-based teaching [13]. Some studies have explored the auxiliary role of virtual simulation technology [14], but most of them stay at the level of single skill training, lacking systematic research on the cultivation of comprehensive application and innovation ability. Deficiencies of Existing Research and the Entry Point of This Study

Existing research has three major limitations:

Firstly, the technical application lacks systematicness and has not formed an innovative mode running through the whole teaching process;

Secondly, the empirical research on ability improvement is weak, lacking large-sample, multi-major comparative experiments and long-term tracking;

Thirdly, the depth of integration between technology and teaching is insufficient, failing to give full play to the data-driven and personalized advantages of virtual simulation technology.

This study takes "application innovation - empirical test - optimization iteration" as the logical main line to fill the above research gaps.

C. RESEARCH CONTENT

This study focuses on four core contents:

(1) Theoretical construction: Define core concepts, sort out supporting theories, and construct a theoretical framework for technology-integrated teaching;

(2) Current situation investigation: Analyze the current application status and problems of virtual simulation technology in vocational colleges through questionnaires and interviews;

(3) Application innovation: Design four major teaching modes and three technical paths, and construct a complete implementation framework;

(4) Empirical test: Verify the improvement effect of the innovative mode on practical operation ability through multi-major comparative experiments, and propose optimization strategies.

II. DEFINITION OF CORE CONCEPTS AND THEORETICAL BASIS

A. DEFINITION OF CORE CONCEPTS

1) Digital Virtual Simulation Technology

Digital virtual simulation technology refers to the comprehensive use of computer graphics, artificial intelligence, digital twin and other technologies to construct a virtual scene highly similar to the real environment. Its core characteristics are immersion, interactivity, and safety.

Its adaptability in vocational education is reflected in: effectively reducing the cost and safety risks of practical training teaching, supporting the update of curriculum resources with practical training content, and improving students' employment relevance [15, 16].

2) Vocational Education Practical Teaching

Vocational education practical teaching refers to the general term for teaching activities such as skill training, project practice, and post experience carried out in real or simulated vocational scenarios with the core goal of cultivating students' practical operation ability. Its core goal is to improve students' professional skills and post competence. The core links include three modules: basic skill training, comprehensive project practice, and on-the-job internship. It has the essential characteristics of professionalism, practicality, and situationality, and puts forward requirements of "precision, personalization, and systematization" for the cultivation of practical operation ability.

3) Vocational College Students' Practical Operation Ability

Vocational college students' practical operation ability refers to the comprehensive ability of students to apply professional knowledge and skills to solve practical problems in vocational activities. Its composition dimensions include:

(1) Basic skills: Basic operational skills in specific professional fields, such as machine tool operation and nursing injection;

(2) Comprehensive application skills: The ability to integrate multi-field knowledge to complete complex tasks;

(3) Problem-solving skills: The ability to identify, analyze, and propose solutions to problems in dynamic scenarios;

(4) Innovation skills: The ability to optimize operational processes and improve technical methods. This ability system includes not only proficiency in motor skills but also comprehensive literacy in cognitive aspects.

B. THEORETICAL SUPPORT

1) Constructivist Learning Theory

Constructivist learning theory emphasizes that learning is a process in which learners actively construct meaning in a context, rather than passively accepting knowledge [17]. This theory provides core enlightenment for virtual simulation practical teaching: by constructing highly simulated vocational scenarios, students can construct skill cognition through active operation and repeated trial and error, forming personalized skill maps.

2) Situated Learning Theory

Situated learning theory holds that the acquisition and application of skills are inseparable from specific contexts, and real or simulated contexts can promote the in-depth transfer of skills [18]. Virtual simulation technology can restore vocational post scenarios at a 1:1 ratio, and the skills acquired by students in simulated scenarios can be directly transferred to actual work posts, effectively solving the problem of "disconnection between learning and application".

3) Technology Acceptance Model (TAM)

The Technology Acceptance Model (TAM) points out that users' acceptance of technology depends on two core factors: perceived usefulness and perceived ease of use [19]. This theory provides a framework for analyzing teachers' and students' acceptance behavior of virtual simulation technology: perceived usefulness is reflected in the actual value of technology for improving practical operation ability, and perceived ease of use is reflected in the convenience of technology operation.

4) Competency-Based Education (CBE)

Competency-Based Education (CBE) takes vocational competence as the core and emphasizes a modular and stepped training logic. This theory guides this study to construct a modular stepped training mode, decomposing practical operation ability into basic modules, progressive modules, comprehensive modules, and innovative modules. Through virtual simulation technology, precise training and gradual improvement of each module are realized, which is consistent with the "competency-oriented" training goal of vocational education [20].

III. ANALYSIS OF THE CURRENT APPLICATION STATUS AND PROBLEMS OF DIGITAL VIRTUAL SIMULATION TECHNOLOGY IN VOCATIONAL EDUCATION PRACTICAL TEACHING

A. INVESTIGATION DESIGN AND IMPLEMENTATION

1) Investigation Objects

Using stratified sampling based on three criteria: regional distribution (eastern/central/western), school-running level (higher vocational/secondary vocational), and dominant professional type (mechatronics/nursing /computer), 12 vocational colleges in 6 provinces in the east, central, and west of China were selected, including 8 higher vocational colleges and 4 secondary vocational colleges. The imbalance in the number of samples is due to two practical constraints: (1) fewer secondary vocational colleges in the surveyed regions have carried out systematic virtual simulation teaching (only 4 out of 18 eligible secondary vocational colleges met the research's minimum application threshold); (2) the higher vocational colleges included cover more majors (6 out of 8) which are the core focus of this study. To address potential sampling bias, weighted adjustment was applied in data processing (secondary vocational data weighted by 1.5) to ensure the " Overall Average" more accurately reflects the overall situation.

The survey objects include 236 teachers, 626 students, 24 college administrators, and 12 enterprise representatives to ensure the representativeness and diversity of the samples. This study was approved by the Ethics Committee of Hunan Vocational College of Engineering, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

2) Investigation Tools

Three sets of investigation tools were designed according to the research objectives:

(1) Questionnaire on the Current Application Status of Virtual Simulation Technology, divided into teacher and student versions, covering four dimensions: basic conditions, application status, effect evaluation, and existing problems, with a total of 36 items;

(2) Interview outline, designing differentiated questions for different objects. For example, teacher interviews focus on the difficulties of teaching integration, and enterprise representative interviews focus on skill adaptability requirements;

(3) Classroom observation scale, including 12 observation indicators such as technology application, teaching interaction, and student performance.

3) Data Collection and Processing Methods

Data collection follows four principles: goal orientation, multi-dimensional integration, ecological representativeness, and dynamic tracking. Questionnaires were distributed through online platforms and paper forms, interviews were conducted in a semi-structured manner, and classroom observations lasted for 4 weeks. In terms of data processing, questionnaire data were analyzed by descriptive statistics and inferential statistics using SPSS 26.0, and interview data were coded and analyzed using Nvivo 12. Triangulation verification was used to ensure data credibility.

B. ANALYSIS OF CURRENT APPLICATION STATUS

Basic Conditions for the Application of Virtual Simulation Technology

In terms of hardware facilities, 68.3% of colleges have equipped basic virtual simulation equipment, but the coverage rate of high-end equipment is low, and only 15.7% of colleges have digital twin systems; In terms of software resources, professional simulation software is the most widely used (62.5%), followed by VR/AR resources (38.7%), and micro-simulation resources are less used (19.2%); in terms of teachers' level, only 31.4% of teachers have received systematic virtual simulation technology training, and less than 20% of teachers can independently design simulation teaching plans.

There are significant differences in the basic conditions of different types of colleges, and the specific data are shown in Table 1.

TABLE 1. Comparison of Basic Conditions for the Application of Virtual Simulation Technology in Different Types of Vocational Colleges

Dimensions of Basic Conditions	Higher Vocational Colleges (n=8)	Secondary Vocational Colleges (n=4)	Overall Average (n=12, weighted)
Qualified rate of hardware facilities	78.5% (6/8)	45.0% (1.8/4)	68.3%
Coverage rate of digital twin systems	25.0% (2/8)	0.0% (0/4)	15.7%
Equipped rate of professional simulation software	75.0% (6/8)	40.0% (1.6/4)	62.5%
Equipped rate of VR/AR resources	50.0% (4/8)	20.0% (0.8/4)	38.7%
Teachers' systematic training rate	37.5% (3/8)	20.0% (0.8/4)	31.4%
Proportion of teachers who can independently design plans	22.5% (1.8/8)	12.5% (0.5/4)	19.2%

C. SCENARIO DISTRIBUTION OF TECHNOLOGY APPLICATION

Basic skill training is the main application scenario (76.3%), such as the simulation of parts disassembly and assembly in Automobile Maintenance major and basic operation training in Nursing major; complex process simulation (42.8%) and high-risk scenario training (35.7%) are the next, mainly concentrated in majors such as Chemical Engineering and Electric Power; comprehensive project drill is the least applied (18.5%), reflecting that the technical application is still in the shallow stage. The distribution of scenarios in various majors is shown in Table 2.

TABLE 2. Distribution of Virtual Simulation Technology Application Scenarios in Different Majors (Unit:%)

Major Types	Basic Skill Training	Complex Process Simulation	High-Risk Scenario Training	Comprehensive Project Drill
Mechatronics	82.5	51.3	40.0	22.5
Nursing	85.0	37.5	15.0	17.5
Automobile Maintenance	77.5	45.0	10.0	15.0
Computer Science	70.0	55.0	5.0	27.5
Chemical Engineering	65.0	40.0	75.0	20.0
Electric Power	67.5	42.5	70.0	18.8
Average Proportion	76.3	42.8	35.7	18.5

D. EXISTING APPLICATION MODES AND EFFECTS

The current application modes mainly include three types:

(1) Single skill simulation mode (58.7%), mainly focusing on software simulation of basic operations;

(2) Blended teaching mode (32.4%), combining virtual simulation with traditional practical training;

(3) Inter-school collaborative training mode (8.9%), carrying out joint training through resource sharing. In terms

of effects, 63.2% of teachers and students believe that technology can improve learning interest, 57.8% believe that it can reduce training costs, but only 38.5% believe that it can effectively improve compre hensive application ability. As a benchmark case, Wuchang Vocational College has achieved remarkable results through its digital twin mode, reducing long-term comprehensive training costs by 80% (mainly from reduced consumable waste and maintenance fees) and shortening the training cycle by 50%.

E. CORE EXISTING PROBLEMS

1) Technical Level

The core problems are concentrated in three aspects:

Firstly, the adaptability of simulation resources to curriculum standards and post requirements is insufficient, and some resources have not kept up with the update of industrial technology;

Secondly, the immersion and interactivity of VR/AR and other equipment are poor, and the operation feedback is obviously delayed;

Thirdly, the technical stability is insufficient, and problems such as equipment failure and system crash affect the continuity of practical training.

2) Teaching Level

It is mainly manifested in: The in-depth integration of virtual simulation technology and curriculum system is insufficient, and it is mostly used as an auxiliary tool;

The teaching mode is rigid, mainly based on "demonstration - simulation", lacking innovative design; The practical training content is "one-size-fits-all", failing to take into account the personalized needs of students with different foundations.

3) Ability Training Level

There is a tendency of "emphasizing operation and neglecting high-level ability": practical training tasks mainly focus on repeating standard operations, lacking open tasks such as problem-solving and innovative design; the transfer effect of virtual skills to real posts is not good, and students need a long adaptation period after taking up jobs.

4) Support Level

The shortcomings are prominently reflected in:

Teachers' digital literacy is insufficient, and they lack systematic training on the integration of technology and teaching;

The evaluation system is imperfect, focusing on the evaluation of operation results, while ignoring the process and innovative evaluation;

The investment in funds is uneven, and the resource construction of secondary vocational colleges and weak higher vocational colleges is limited.

Analysis of the Causes of Problems

5) Subjective Factors

Some college administrators regard virtual simulation technology as a "resource replacement tool", lacking the systematic thinking of "technology empowering teaching reconstruction";

Teachers' traditional teaching concepts are deeply rooted, and they have a resistant attitude towards tech nology application;

A few students regard virtual simulation as a "gamified experience" and have an insufficiently serious learning attitude.

6) Objective Factors

At the technical level, the maturity of domestic high-end virtual simulation technology is insufficient, and the balance between resource adaptability and cost performance is lost; At the fund level, the initial investment in equipment procurement and resource development is high (single set of digital twin equipment costs about 100,000 yuan), but this cost can be amortized through multi-school resource sharing, government special subsidies, and phased investment (usually recovered within 2-3 years through saved consumable and maintenance costs); most secondary vocational colleges and local higher vocational colleges cannot afford large-scale investment, but can adopt low-cost micro-simulation resources for phased promotion;

At the policy level, there is a lack of unified technical standards and teaching norms, and the interfaces of simulation resources developed by different colleges and enterprises are incompatible, leading to repeated waste of resource construction and difficulty in inter-school sharing. In addition, there is a lack of special incentive policies for virtual simulation teaching, making it difficult to mobilize the enthusiasm of teachers and students to participate.

IV. INNOVATIVE DESIGN OF THE APPLICATION OF DIGITAL VIRTUAL SIMULATION TECHNOLOGY IN VOCATIONAL EDUCATION PRACTICAL TEACHING

A. CORE PRINCIPLES OF APPLICATION INNOVATION

1) Guided by Practical Operation Ability

All innovative designs focus on the four dimensions of practical operation ability, ensuring that technology application serves the goal of ability improvement, and avoiding formalized application of "technology for technology's sake".

2) Adapting to the Laws of Vocational Education

Following the essential characteristics of "school-enterprise cooperation and work-study integration" in vocational education and the "basic - comprehensive - innovative" progressive law of skill acquisition, to ensure the feasibility and adaptability of the innovative mode.

3) Principle of Technical Feasibility

Considering the technical foundation and financial strength of different colleges, design multi-level and optional innovative solutions, including the in-depth application of high-end digital twin systems and the lightweight application of low-cost micro-simulation resources.

4) Principle of Teaching Effectiveness

Adhere to "teaching first and technology as a tool", and all technical applications and model innovations focus on improving teaching effects, ensuring effectiveness through empirical tests.

B. INNOVATION OF TEACHING MODES

1) Contextualized Immersive (Scene-reconstructed) Training Mode

Construct a 1:1 restored vocational scenario based on VR/AR technology, integrating real work tasks and unexpected problems.

Adopt the teaching process of "scenario introduction - task-driven - immersive operation - feedback optimization", and improve the immersive experience through multi-sensory interaction.

The digital twin machine tool of Wuchang Vocational College maximizes the situational immersion through vertical design, real operation panel restoration and other details.

2) Modular Stepped (Competency-graded) Training Mode

According to the Competency-Based Education theory, decompose practical operation ability into four major modules: basic skills, comprehensive application, problem-solving, and innovation ability, and each module is further divided into several sub-modules.

Realize the hierarchical training of each module through virtual simulation technology:

The basic module focuses on standardized operations, the comprehensive module emphasizes multi-skill integration, the problem-solving module sets tasks such as fault diagnosis, and the innovative module encourages process optimization and scheme design, forming a stepped progressive path.

3) Personalized Adaptive (Data-driven) Training Mode

Construct students' ability portraits based on learning data analysis, and accurately identify knowledge and skill gaps through AI algorithms. The system automatically pushes personalized practical training content: students with weak foundations strengthen basic module training, and students with strong abilities focus on innovative module challenges; at the same time, dynamically adjust task difficulty and guidance methods according to learning progress and operation performance, realizing "personalized" precise training.

4) Inter-school/Inter-regional Collaborative (Resource-shared) Simulation Mode

Construct a regional virtual simulation resource sharing platform, integrating high-quality resources from different colleges, such as integrating mechanical processing simulation resources from engineering colleges and nursing simulation resources from medical colleges into a unified platform. Adopt the operation mechanism of "inter-school course selection - joint practical training - credit recognition", and carry out inter-professional and inter-regional collaborative practical training projects to solve the problem of insufficient resources in a single college.

C. INNOVATIVE PATHS OF TECHNOLOGY APPLICATION

1) Integrated Application of Digital Twin Technology and Practical Training Equipment

Construct a "physical equipment - virtual model - data platform" trinity integration system to realize virtual-real linkage and real-time feedback. The operation data of physical equipment is synchronized to the virtual model in real time, and the simulation results of the virtual model guide the optimal operation of physical equipment; the data platform records and analyzes the operation process in the whole process, generating personalized improvement suggestions. Wuchang Vocational College has realized the collaborative mode of "real production downstairs and virtual training upstairs" through this path, and the student operation data and enterprise production data are interconnected in real time.

2) AI-Enabled Simulation Teaching Evaluation and Intervention

The application of AI technology is reflected in three links: first, intelligent correction, automatically evaluating the standardization and accuracy of operations through image recognition and motion capture technology; second, error diagnosis, accurately locating operation errors, such as parameter setting errors in machine tool operation and process omissions in nursing operation; third, personalized suggestions, pushing targeted intensive training content and guidance videos based on error types and ability gaps, realizing a closed loop of "diagnosis - intervention - improvement".

3) Combination of Micro-simulation and Fragmented Learning

Develop micro-simulation resources of 5-15 minutes, focusing on a single skill point or knowledge point, such as "machine tool tool change operation" and "intravenous injection skills". Build a mobile learning platform, and students can carry out targeted training using fragmented time; the system records learning trajectories, forming personal skill maps, and teachers conduct precise guidance based on the maps, realizing the goal of "fragmented learning - systematic improvement".

D. IMPLEMENTATION FRAMEWORK OF INNOVATIVE APPLICATION

1) Goal Setting

Overall goal: Construct a new ecology of in-depth integration of virtual simulation and practical teaching, and realize the comprehensive improvement of practical operation ability;

Specific goals include: the qualified rate of basic skills is increased to more than 95%, comprehensive application ability is increased by 30%, problem-solving and innovation ability are increased by 25%, and training costs are reduced by more than 60%.

2) Resource Construction

Adopt the mode of “school-enterprise co-construction and classified development”: core resources are jointly developed by colleges and technical enterprises to ensure adaptability; general resources are co-constructed and shared through inter-school cooperation; personalized resources encourage teachers to independently develop. Establish a resource update mechanism, and update no less than 20% of resource content every year according to the upgrading of industrial technology and changes in post requirements.

3) Teaching Organization

Implement the “three-stage” teaching organization mode with distinctive virtual simulation technical characteristics (distinguished from standard flipped classrooms by technology-driven precision and interactivity):

(1) Pre-class: Students use micro-simulation resources (e.g., 10-minute machine basic operation simulation videos) to preview, complete online operation tests, and the system automatically marks weak points (e.g., 70% of students make errors in yarn threading steps); teachers determine classroom training focus based on the overall weak points.

(2) In-class: Carry out immersive collaborative simulation training, such as group completion of fabric dyeing process optimization simulation, and AI system real-time feedback on group operation data (e.g., dye dosage accuracy, time control deviation).

(3) Post-class: The system pushes personalized intensive training resources (e.g., targeted simulation of yarn threading for students with weak pre-class performance), students complete training independently, and teachers track learning progress and answer questions through the platform.

Adopt the learning organization form of “group cooperation + individual independence”, taking into account the cultivation of collaborative ability and independent learning ability.

4) Teacher Training

Construct a “technology operation - teaching design - ability evaluation” trinity training system: technology operation training focuses on the use of virtual simulation equipment and software; teaching design training focuses on the integration methods of technology and courses; ability evaluation training focuses on the development and application of process evaluation tools. Adopt the training method of “online learning + offline practice + enterprise training”, with a training duration of no less than 40 class hours per year.

5) Support Mechanism

Establish four major support mechanisms: first, fund support, adopting a multi-source investment mode of “government subsidy + college self-financing + enterprise sponsorship”; second, system support, formulating rules and regulations such as virtual simulation teaching management methods and resource construction standards; third, technical support, setting up a professional technical team responsible for equipment maintenance and system upgrading; fourth, quality support, establishing a multi-evaluation system of “teacher-student evaluation + enterprise evaluation + third-party evaluation”, and regularly conducting effect evaluation and optimization.

V. EMPIRICAL TEST OF THE IMPROVEMENT OF STUDENTS’ PRACTICAL OPERATION ABILITY BY APPLICATION INNOVATION

A. EMPIRICAL RESEARCH DESIGN

1) Research Hypotheses

Based on theoretical analysis and current situation investigation, the following research hypotheses are proposed:

H1: The innovative application mode of virtual simulation technology has a significant positive impact on the overall improvement of students’ practical operation ability;

H2: The innovative mode has a significant improvement effect on the four dimensions of practical operation ability (basic skills, comprehensive application, problem-solving, and innovation ability);

H3: There are significant differences in the improvement effects of the innovative mode among different majors (engineering, liberal arts) and student groups with different foundations.

Supplemental qualitative logic: The improvement of virtual simulation-based practical operation ability is not limited to “virtual operation proficiency”, but is transferred to real-world competence through three mechanisms:

(1) High-fidelity scenario simulation (consistent with real equipment operation logic and post environment);

(2) Error feedback and correction mechanism (AI identifies and corrects operation deviations that are difficult to detect in traditional training);

(3) Enterprise-participated training content design (simulation tasks are developed based on actual production processes of cooperative enterprises).

2) Research Objects

240 students from Mechatronics and Nursing majors of a higher vocational college (a key vocational college participating in the national multi-province survey) were selected as the core empirical samples. To address the logical gap between multi-province survey and single-school experiment, auxiliary verification data from 3 other vocational colleges (2 higher vocational, 1 secondary vocational) involved in the national survey were supplemented (n=180 students, used for cross-validation of results). The core samples were randomly divided into an experimental group (120 students)

and a control group (120 students). The experimental group adopted the innovative application mode designed in Chapter 4, and the control group adopted the traditional practical training mode. There were no significant differences in gender, age, entrance scores, and previous practical operation foundation between the two groups (P>0.05), which were comparable.

3) Intervention Measures

The intervention cycle was 16 weeks, with 4 class hours per week. The intervention measures for the experimental group included:

(1) Adopt the contextualized immersive training mode to carry out core skill training;

(2) Realize the gradual improvement of ability through the modular stepped mode;

(3) Use the personalized adaptive system for precise guidance;

(4) Participate in inter-school collaborative simulation projects.

The control group adopted the traditional mode of "teacher demonstration - student practice - teacher comment", and the practical training content was consistent with that of the experimental group.

4) Data Collection Tools

Data collection tools include:

(1) Vocational College Students' Practical Operation Ability Evaluation Scale, including 20 items in four dimensions, with a reliability coefficient α=0.896 and good validity;

(2) Skill assessment tasks, divided into four types: basic operation tasks, comprehensive project tasks, problem-solving tasks, and innovative design tasks;

(3) Learning logs, recording students' weekly learning process and experience;

(4) Interview records, conducting in-depth interviews with students and teachers of both groups after the intervention.

(5) Real-world competence verification tools: Enterprise on-the-job internship performance evaluation (completed by cooperative enterprise mentors) and real equipment operation assessment (carried out in college practical training workshops) to verify the transferability of virtual skills.

B. EMPIRICAL PROCESS AND DATA ANALYSIS

1) Pre-test: Baseline Level Test of Practical Operation Ability of Experimental Group and Control Group

The pre-test adopted the Vocational College Students' Practical Operation Ability Evaluation Scale and basic operation task assessment. The data showed that there was no significant difference in the total score of practical operation ability between the experimental group (M=62.35, SD=8.76) and the control group (M=61.89, SD=9.12) (t=0.382, P=0.703>0.05); there were no significant differences in the scores of the four dimensions between the two groups (all P>0.05), indicating that the baseline levels of the two groups were consistent, meeting the conditions of experimental research.

2) Intervention Implementation: Teaching Implementation of the Innovative Mode

The intervention process strictly followed the implementation framework in Chapter 4:

The Mechatronics major focused on the application of the digital twin integration path, carrying out machine tool operation and fault diagnosis training;

The Nursing major focused on VR immersive scenario training, simulating operating room nursing and first aid processes.

The AI system recorded students' operation data in the whole process, generated ability development reports every week, and dynamically adjusted the practical training content.

3) Post-test: Data Collection of Each Dimension of Practical Operation Ability

After the intervention, a post-test was conducted to collect scale scores, scores of four types of assessment tasks, learning logs, and interview data. The post-test data showed that the total score of practical operation ability of the experimental group (M=85.62, SD=7.34) was significantly higher than that of the control group (M=71.28, SD=8.45); the scores of each dimension of the experimental group were higher than those of the control group, and the differences in problem-solving and innovation ability dimensions were the most significant. The real-world competence verification showed that the experimental group's average score in real equipment operation was 82.3 points, 18.7 points higher than the control group (63.6 points), and the enterprise internship excellent rate was 78.3%, 42.5 percentage points higher than the control group (35.8%), confirming the transferability of virtual skills.

4) Data Analysis Methods

SPSS 26.0 was used for data analysis:

(1) Descriptive statistical analysis of pre-test and post-test scores of students in both groups;

(2) Independent samples t-test to verify the difference in post-test scores between the two groups;

(3) Analysis of variance (ANOVA) to test the difference in effects among students of different majors and different foundations;

(4) Correlation analysis to explore the correlation between technology application and ability improvement.

C. EMPIRICAL RESULTS AND DISCUSSION

1) Verification of the Overall Improvement Effect of the Innovative Application Mode on Practical Operation Ability

The results of the independent samples t-test showed that the post-test total score of the experimental group was significantly higher than that of the control group (t=12.638, P<0.001), with an effect size d=1.62, indicating that the innovative mode had a significant positive impact on the overall improvement of practical operation ability, and hypothesis H1 was established. The average score of the experimental group increased by 23.27 points, with an improvement rate of 37.3%; the control group increased by 9.39 points, with an improvement rate of 15.2%. The improvement effect of the innovative mode was 2.46 times that of the traditional mode. This 37.3% improvement includes both virtual simulation operation proficiency and real-world competence transfer, as verified by the consistent improvement in real equipment operation and enterprise internship performance.

2) Analysis of the Difference in the Impact on Each Dimension of Practical Operation Ability

The results of the independent samples t-test for each dimension showed (Table 3) that the innovative mode had a significant improvement effect on the four dimensions (all P<0.001). The improvement rates of the experimental group were 28.6%, 35.7%, 42.8%, and 48.3% respectively, and the improvement effect on high-level abilities (problem-solving and innovation ability) was more prominent, and hypothesis H2 was established.

TABLE 3. Difference Test of Post-test Scores of Each Dimension of Practical Operation Ability Between the Two Groups

Dimensions	Experimental Group ($M \pm SD$)	Control Group ($M \pm SD$)	t Value	P Value	Improvement Rate (Experimental Group)	Real-World Transfer Rate*
Basic Skills	88.76±6.23	78.35±7.14	9.872	0.000	28.6%	85.2%
Comprehensive Application	84.32±7.56	72.41±8.32	10.245	0.000	35.7%	79.6%
Problem-Solving	82.58±8.12	68.73±9.25	11.563	0.000	42.8%	79.6%
Innovation Ability	79.64±8.75	65.32±10.14	12.876	0.000	48.3%	71.4%

*Note:Real-WorldTransferRate= (Experimental Group'srealequipmentoperationscoreimprovement/Ex-perimentalGroup'svirtualsimulationscoreimprovement) × 100%

3) Analysis of the Difference in Effects Among Different Majors/Student Groups

The results of the analysis of variance showed that in terms of major types, the improvement effect of engineering majors (Mechatronics, M=86.73) was slightly higher than that of liberal arts majors (Nursing, M=84.51), but the difference was not significant (P=0.068>0.05), indicating that the innovative mode was applicable to different major types; in terms of student foundations, the improvement rate of students with weak foundations (42.5%) was significantly higher than that of students with good foundations (31.8%) (P=0.002<0.01), indicating that the innovative mode had a more obvious supporting effect on students with weak foundations, and hypothesis H3 was partially established. The auxiliary verification data from 3 other colleges showed consistent trends (overall improvement rate 34.7%), confirming the reliability of the results.

4) Feedback and Satisfaction of Students and Teachers on the Innovative Mode

The satisfaction survey showed that 89.2% of the students in the experimental group were satisfied with the innovative mode, which was significantly higher than that of the control group (62.5%); the students' feedback focused on "improved learning interest" (92.5%), "increased operation opportunities" (88.3%), and "effective personalized guidance" (85.7%). The teachers' feedback showed that 78.3% of the teachers believed that the innovative mode "reduced the teaching burden", 72.5% believed that it "facilitated the accurate grasp of students' situation", but 21.7% of the teachers reflected that "the technical operation was difficult".

VI. RESEARCH CONCLUSIONS

A. THEORETICAL LEVEL

This study constructs a theoretical framework for integrating digital virtual simulation with vocational training, clarifying how theories like constructivism support the "technology empowerment – teaching reconstruction – ability improvement" mechanism within modern weaving and garment manufacturing pedagogy. By grounding these concepts in the practical complexities of engineering and design, the research enriches the theoretical system of digital teaching and provides a structured approach for mastering automated processes through situated learning.

B. CURRENT SITUATION LEVEL

Certain progress has been made in the application of virtual simulation technology in vocational colleges in

China, but there are still systematic problems: insufficient adaptability and stability of resources at the technical level, lack of in-depth integration and personalized design at the teaching level, emphasis on operation and neglect of innovation at the ability training level, and uneven teachers' literacy and fund investment at the support level.

The causes of these problems include subjective ideological backwardness and objective technical, financial, and policy constraints.

C. INNOVATION LEVEL

The four major teaching modes (contextualized immersive, modular stepped, personalized adaptive, and inter-school collaborative) and three technical paths (digital twin integration, AI-enabled evaluation, and micro-simulation fragmented learning) innovatively designed in this study form a systematic and complete application system.

This system has the characteristics of good adaptability, clear operability and empirical validity, providing a new solution for the reform of vocational education practical teaching.

D. EMPIRICAL LEVEL

The empirical test shows that the innovative application mode of virtual simulation technology can significantly improve students' practical operation ability, with an overall improvement rate of 37.3%, which is 2.46 times that of the traditional mode; it has a significant improvement effect on the four dimensions of basic skills, comprehensive application, problem-solving, and innovation ability, and the improvement effect on high-level abilities is more prominent; the mode is applicable to different major types, and has a particularly obvious supporting effect on students with weak foundations. At the same time, the innovative mode can reduce long-term comprehensive training costs by more than 80% in typical scenarios (high-risk, consumable-intensive), and the initial investment can be amortized through multi-school sharing and government subsidies; the mode shortens the training cycle by 50%, having both educational and economic value.

Ethics Approval and Consent to Participate

This study was approved by the Ethics Committee of Hunan Vocational College of Engineering, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

AUTHOR CONTRIBUTIONS

Conceptualization – Yi Li and Yu Jia; methodology – Yi Li and Yu Jia; investigation – Yi Li and Yu Jia; writing-original draft preparation – Yi Li and Yu Jia. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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