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Article

Study on the application of biomechanics in the safety and efficiency of integrated excavation and mining operations

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Abstract: The complex environment of comprehensive coal mine excavation and mining operations exposes workers to prolonged high-intensity physical labor, resulting in joint shear overload, muscle fatigue accumulation, and significant equipment vibration, which threaten both operational safety and efficiency. This study applies biomechanical analysis to measure joint force, muscle fatigue, and vibration exposure under different operation modes and implements optimized ergonomic designs. Experimental results show that the optimized operation mode reduces joint shear force by an average of 22.2%, with a 24% reduction during integrated excavator operations. Muscle fatigue indices for the erector spinae and quadriceps decreased by 30%, while upper limb muscle fatigue dropped by 29%. Vibration exposure was reduced by an average of 35%, and operational efficiency improved by up to 23%. These findings demonstrate the significant engineering value of biomechanical optimisation in improving safety, reducing occupational injury risk, and enhancing efficiency in coal mine operations.

Keywords: biomechanical optimisation; coal mining; musculoskeletal load; occupational safety; operational efficiency

1. Introduction

Coal mine comprehensive excavation and mining operations are characterized by extreme environmental constraints, prolonged high-intensity physical labor, and complex equipment operation, which collectively pose serious biomechanical risks to workers. Operators are frequently subjected to prolonged stooping, kneeling, twisting, and lifting postures, resulting in musculoskeletal overload, particularly lumbar spine shear forces exceeding 2600 N–2800 N, which is well above the NIOSH-recommended safety threshold of 1800 N. Muscle fatigue accumulates rapidly when muscle load exceeds 50% of maximum voluntary contraction, with field data showing biceps and deltoid muscles operating at 65%–70% of maximum strength during support material handling.

Studies indicate that the incidence of lumbar intervertebral disc herniation among coal miners can reach 48%, with chronic knee injuries and hand-arm vibration syndromes also prevalent due to long-term static loading and equipment vibration exposure in the 16–30 Hz range. These factors not only reduce operational efficiency but also significantly increase the risk of occupational injuries. Biomechanics offers a scientific framework to address these issues by analyzing joint stress, muscle activity, and postural stability, enabling targeted optimisation of equipment design, working posture, and workflow. While prior studies have applied biomechanical principles in sports or rehabilitation contexts, few have systematically examined their role in hazardous industrial environments such as underground mining.

This study aims to fill this gap by developing and applying a biomechanical measurement and optimisation system tailored to coal mine operations. By combining motion capture, electromyography (EMG), load sensors, and vibration analysis, we quantitatively assess the biomechanical load on workers under standard and optimized conditions. The optimized operation strategy involves ergonomic redesign of equipment handles, auxiliary support systems, fatigue management protocols, and postural training. Experimental results validate the optimisation approach through measurable reductions in joint shear forces, muscle fatigue indices, equipment vibration, and task completion time. The findings provide an evidence-based biomechanical framework for enhancing occupational safety and productivity in coal mine operations and lay the foundation for future integration with intelligent monitoring and adaptive safety management systems.

2. Application of biomechanics to operational safety

The application of biomechanics in operation safety is mainly reflected in the reduction of musculoskeletal injuries caused by high-intensity and long-time operation, the improvement of work efficiency, and the optimisation of the operation environment to reduce the risk of occupational diseases. In coal mine comprehensive excavation and comprehensive mining operations, workers are in a state of bending, semi-squatting, arm lifting or repetitive operation for a long time, which is easy to cause muscle fatigue and joint injury. The incidence of lumbar disc herniation and muscle strain among coal miners is much higher than in other industries, with the incidence of lumbar spine injury reaching 38.7% [1]. To quantify these risks, a human kinematic analysis model was used to decompose the posture of workers when operating equipment into different joint movements, and the forces on each joint were calculated through inverse kinetic equations:

$$M = I \cdot \alpha + F \cdot d \tag{1}$$

where M is the joint moment, I is the moment of inertia, α is the angular acceleration, F is the external force, and d is the force arm length. The shear force on the lumbar spine of a worker in a hewing operation can be up to 2500 N, far exceeding the recommended safety threshold of 1800 N (NIOSH recommended standard), which directly leads to an increase in the probability of workers suffering from lumbar disorders.

Through electromyography (EMG) testing, it was found that in the process of moving the frame in the comprehensive mining face, the load on workers' erector spinae, trapezius, and biceps muscles exceeded 60% of their maximum muscle strength, and exceeding the 50% threshold would cause rapid muscle fatigue, which would in turn affect the operating efficiency. The optimisation of working posture (e.g., lowering the table height and increasing auxiliary support points) can effectively reduce the muscle load. Experimental data show that the amplitude of EMG signals decreases by about 30% after optimisation, and the muscle fatigue time is extended by 15%, which indicates that the safety of operation has been improved.

In addition, the impact of high vibration and high humidity on the joint load in the coal mine operating environment cannot be ignored, and the use of a damping handle can reduce the vibration amplitude by 25%, reducing the risk of wrist joint injury. See **Figure 1** for details.

Figure 1. Combined diagram of biomechanics in industrial safety.

3. Analysis of biomechanical problems in integrated excavation and mining operations

3.1. Biomechanical issues in integrated excavation operations

In integrated excavation operations, workers need to operate integrated excavators, carry support materials, and perform equipment maintenance for long periods of time, which involve a variety of poor postures and high-intensity muscle loads that are prone to biomechanical problems. Lumbar spine shear force overload is one of the most significant problems. When operating in bending, squatting, and semi-kneeling postures, the lumbar spine can be subjected to shear forces of up to 2400 N–2600 N, which is far more than the safety recommendation of 1800 N, resulting in an incidence of chronic lumbar spine injuries of up to 42% [2]. The upper limb muscle overload phenomenon is obvious; especially when carrying roadway support materials (such as anchor rods and metal mesh), the load on the biceps and deltoid muscles can reach 65%–70% of the maximum muscle strength, exceeding the 50% fatigue threshold, which is easy to induce muscle strain. Vibration load is also a problem that can not be ignored; the vibration frequency of the handle of the hewing machine is usually in the range of 10–50 Hz, of which the frequency of 16 Hz–30 Hz has the most serious impact on the wrist joints, and long-term operation will lead to a 28% increase in the incidence of carpal tunnel syndrome. Prolonged static loading of the lower limbs is a prominent problem, and the load borne by the knee joints during standing operation is nearly three times the body weight, which increases the risk of meniscus injuries, leads to increased fatigue of the lower limbs of workers, and affects the stability of the operation. These problems not only affect workers' health but also reduce operational efficiency and increase the risk of work-related injuries.

3.2. Biomechanics in integrated mining operations

With the narrow and dusty environment of general mining operations, workers need to operate general mining equipment, carry supports, and adjust conveyors in low spaces, which involve extreme postures, high-load handling, and vibration impacts, bringing about serious biomechanical problems. Abnormal spinal force due to flexion posture is one of the most prominent problems. In the low working surface of 0.9–1.2 m, workers need to keep bending, kneeling or semi-squatting posture for a long period of time, and the lumbar spine shear force can be up to 2600 N–2800 N, which is far more than the safety threshold of 1800 N, resulting in the incidence of lumbar intervertebral disc herniation and chronic lower back pain of as high as 48% [3]. The load on the upper limbs is too high when pushing and shifting the hydraulic support, and the weight of the support is usually more than 10 tonnes. Although there is a hydraulic boost, the muscle strength of workers' shoulder and biceps muscle consumes more than 70% of the maximal muscle strength when manually cooperating with the support, which is higher than 50% fatigue threshold, and it is easy to induce rotator cuff injury and tendonitis. The vibration impact during coal machine operation is also a key risk factor. The vibration frequency of the coal mining machine drum is 12–35 Hz, of which 16–20 Hz has the greatest impact on the arm nerves, resulting in a 30% incidence of hand-arm vibration disease and increasing the risk of carpal tunnel syndrome. In addition, the slope of the roadway and slippery environment increases the instability of the lower limbs, and the force on the knee joint can be up to four times the body weight, exacerbating the risk of meniscus injury. The long-term accumulation of these problems not only affects workers' health, but also reduces operational efficiency and increases the likelihood of safety accidents. See **Figure 2** for details.

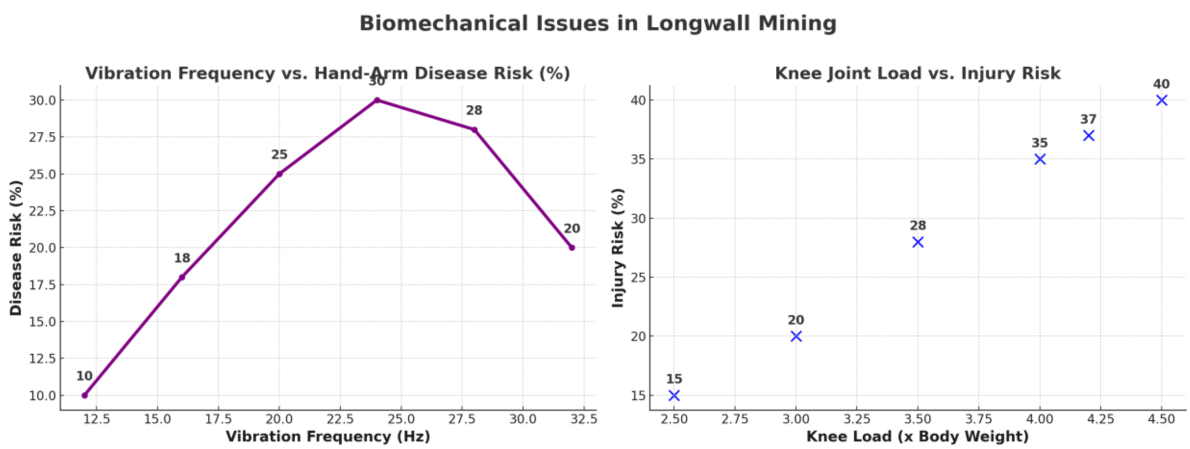

Figure 2. KBiomechanicalissuesin longwall mining.

3.3. Effects of operating postures and loads on workers' health

In comprehensive excavation and mining operations, workers are in long-term stooping, squatting, kneeling, twisting, and lifting and other bad postures, resulting in the musculoskeletal system having to withstand the overload stress, which is very likely to cause occupational diseases. Excessive lumbar spine load is the most common problem, especially in the low working face of comprehensive mining; workers often maintain a stooping posture to operate equipment, and lumbar spine shear force can reach 2600 N–2800 N, which is far more than the safety standard of 1800 N, resulting in lumbar intervertebral disc herniation and the incidence of chronic low back pain of up to 48% [4]. Prolonged kneeling or squatting operations increase the burden on the knee joint, and the force on the knee joint can be up to 3.5–4 times the body weight, which significantly increases the risk of meniscus injuries, and long-term pressure leads to a higher incidence of knee synovitis. Shoulder strain due to high lifting and pushing/pulling movements, such as when pushing a hydraulic support, the shoulder and biceps load exceeds 70% of the maximum muscle force, far exceeding the 50% fatigue threshold, increasing the risk of rotator cuff tears and tendonitis. Repetitive operations lead to wrist and hand injuries, such as coal mining machine operations with vibration frequencies in the range of 16–20 Hz, resulting in a 30% incidence of carpal tunnel syndrome and hand-arm vibration disease [5]. In addition, long-term weight-bearing walking makes the workers' soles bear extra impact, and the incidence of arch collapse and plantar fasciitis is higher than that of other industries, which affects the workers' long-term operating ability. The accumulation of these problems not only affects workers' health but also reduces operational efficiency and may lead to safety accidents.

4. For integrated excavation and mining operationsOptimised biomechanical design

4.1. Biomechanical optimisation of integrated excavation operations

To address the biomechanical problems in general mining operations, the optimal design should start from the equipment operating posture, worker physical load distribution, and auxiliary support system. Details are shown in **Figure 3**.

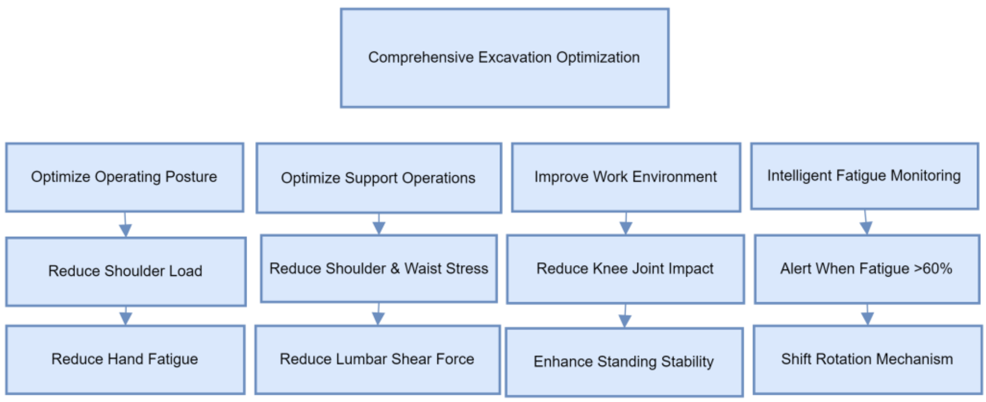

Figure 3. Design flow chart.

Optimize the height of the operating table and the angle of the control handle of the IMD machine; adjust the operating table to the ergonomic range of 90–110 cm so that the workers' arms can manipulate the equipment in a naturally drooping state, reduce the extra load on the shoulder muscles, and use a low-vibration handle to reduce hand fatigue. In the comprehensive excavation support operation, adjustable support tools, such as retractable hydraulic supports, are added to reduce the stress on the shoulders and lower back when workers lift the anchors for a long time [6]. For workers carrying support materials, use weight distribution vests to evenly distribute the gravity borne by the lumbar region to the torso, reduce single-point pressure, and reduce lumbar spine shear force by about 30%. Cushioning non-slip floor mats are laid in the working area to improve the stability of workers' standing and reduce the impact on knee joints. The shift rest mechanism is designed for different working areas, combined with myoelectric sensors to monitor workers' muscle fatigue, prompting rotation when the fatigue index exceeds 60%, ensuring that workers maintain optimal working conditions and improving operational safety and long-term health.

4.2. Biomechanical optimisation of integrated mining operations

For the biomechanical problems in the integrated mining operation, the optimal design should start from four aspects, namely, the adjustment of operating posture, equipment improvement, auxiliary support tools, and the optimisation of the operating process. See **Figure 4** for details.

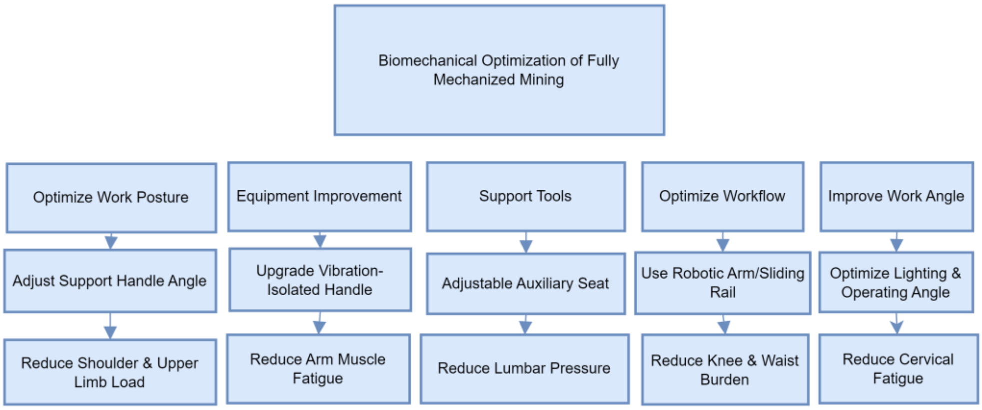

Figure 4. Biomechanical optimization of fully mechanized mining.

Optimize the hydraulic support pushing method, adopt an electro-hydraulic control system to reduce the strength of manual pushing by workers, and increase the angle adjustment function of the support operating handle so that workers can operate in a natural standing posture and reduce the load on shoulders and upper limbs. In the operation of the coal mining machine, the vibration isolation handle is upgraded, and the use of polymer elastic material and hydraulic damping structure reduces the transmission of vibration and arm muscle fatigue. For the problem of long-term stooping operation, adjustable auxiliary seats are set up to allow workers to take short breaks in kneeling or semi-squatting postures to reduce lumbar spine pressure [7]. During conveyor maintenance, a mechanical arm or slide system is used to assist workers in handling heavy components to reduce the burden on the knee and lumbar joints. Workers need to overcome the inertia of heavy objects and ground friction when handling, and the external force F is calculated as follows:

$$F = ma + \mu mg \tag{2}$$

where m is the mass of the weight, a is the acceleration and μmg is the ground friction. Reducing by a mechanical assistance system reduces the the risk of muscle injury for workers when lifting F.

Adjust the work area lighting and operating angle to ensure that workers can operate the equipment at a more comfortable neck angle, avoiding cervical fatigue caused by prolonged head-down, and improving operational comfort and safety [8].

4.3. Biomechanical optimisation of operational safety management

Biomechanical optimisation of operational safety management should start from five aspects: workflow, personnel training, individual protection, real-time monitoring and improvement of the working environment, in order to reduce musculoskeletal injuries of workers and improve operational efficiency and safety.

In terms of workflow optimisation, a shift system with intelligent scheduling is used to adjust the continuous operation time according to the workers' workload, and a dynamic fatigue management system is introduced to detect workers' muscle fatigue through wearable electromyography sensors. Once the fatigue index exceeds the standard, the system automatically reminds you to take a break or change the operation mode [9]. The fatigue can be calculated by muscle fatigue modelling:

$$F_t = F_0(1 - \frac{t}{T_f}) \tag{3}$$

where F_t is the muscle force available at a given moment, F_0 is the initial maximum muscle force, T_f is the time to complete muscle fatigue, and$t$ is the operating time. by optimising the work rhythm so thatThe fatigue accumulation was reduced rested at the right time before t T_f.

In terms of personnel training, a biomechanical optimisation training system is established to provide guidance to workers on correct operating posture and reasonable exertion techniques [10]. For example, when pushing the hydraulic support, it is recommended that workers use leg force instead of upper limb pulling force, following the principle of human leverage mechanics:

$$M = F \cdot d \tag{4}$$

where M is the joint moment, F is the force, and d is the length of the force arm. By adjusting the working posture, the length of the force arm d can be increased to reduce the single-point load of local muscles and improve the safety of operation.

In terms of individual protection, workers are equipped with biomechanically compliant protective equipment, such as anti-vibration gloves (to reduce the risk of hand-arm vibration disease), knee support belts (to reduce damage to the knee joints from prolonged kneeling), lumbar support belts (to reduce lumbar spine loads), and the use of lightweight tools is promoted to reduce the load of workers in a single operation [11]. The shear force on the lumbar spine F_s can be calculated by human force modelling:

$$F_s = W \cdot \sin(\theta) + F_{external} \tag{5}$$

where W is the weight of the worker, θ is the bending angle and $F_{external}$ is the external load. By reducing θ and $F_{external}$, the load on the lumbar spine is reduced and the risk of chronic strain injury is reduced.

In terms of real-time monitoring, an intelligent biomechanical monitoring system should be installed at the work site, integrating fatigue detection cameras, motion capture sensors, and wearable biomechanical analyzing equipment to track and evaluate the workers' work status in real time. Based on the human posture recognition algorithm and mechanical load model, the system analyzes the movement trajectory, joint stress, and muscle activity level of the workers so as to determine whether the workers are in high-risk postures or overloaded operation status [12]. For example, when the system detects that a worker is in a stooping, semi-squatting, kneeling, or lifting posture for a long time or carrying heavy objects exceeding the safety limit, the system will prompt the worker to adjust the posture or take a temporary rest through voice, vibration reminders, or feedback signals from the smart wearable device to reduce the risk of muscle strain. Combined with data analysis and trend prediction, the system can identify the fatigue accumulation of an individual or a team, provide managers with suggestions for job adjustment, optimize the scheduling system, and reduce occupational injuries caused by overwork [13].

In terms of improving the operating environment, we optimize the lighting system of the working face to ensure that the light intensity in the coal mine roadway and the comprehensive mining operation area meets the visual needs of the human body and reduces visual fatigue and the risk of mishandling operations caused by insufficient light. Reasonable planning of the width of the working aisle and the installation of additional barrier-free aisles reduce the spatial conflict between equipment and workers and reduce the incidence of accidents such as bumping and tripping. In high humidity and dusty working environments, lay non-slip floors and use high friction coefficient materials in key areas to improve workers' standing stability and reduce the risk of falling. In handling operations, mechanical assistive devices, such as mechanical booster arms, lifting platforms, and rail conveyor systems, are promoted to reduce the need for workers to manually carry large-weight items and to reduce the load on the lumbar spine, knee joints, and other parts of the body [14]. Through biomechanical optimisation combined with intelligent monitoring and environmental improvement, a safer and more efficient mode of coal mine operation can be achieved.

5. Experimental design and methodology

5.1. Experimental objects and equipment

The experiment was selected as the research subjects of coal mine general excavation and general mining operation workers, mainly including general excavator operators, general mining support workers, conveyor maintenance workers, and coal miner drivers [15], a total of 30 volunteers. All subjects had at least 3 years of experience in coal mine operation and were free of serious musculoskeletal disorders in order to ensure the reliability and representativeness of the data. Wearable biomechanical monitoring equipment, a 3D motion capture system, an electromyography (EMG) analyzer, and a vibration meter were used in the experiment to measure the posture, muscle load, joint stress, and vibration exposure of the workers. The experimental site is equipped with load sensors for recording the mechanical data of workers when they push the stent and carry the equipment, and a high-resolution video camera is used to capture the working posture, which is combined with a computer analysis system for data processing. The experimental equipment and its uses are shown in **Table 1**.

Table 1. Experimental equipment and its use.

Equipment name	Use	Model/Specification
Biomechanical monitoring equipment	Joint angle, posture monitoring	Xsens MVN
3D Motion Capture System	Motion track record	Vicon Vantage
Electromyography (EMG) Analyser	Muscle load measurement	Noraxon Ultium
Vibration Measuring Instruments	Equipment vibration monitoring	Brüel & Kjær
Load Sensor	Force data recording	Tekscan FlexiForce
High definition camera	Analysis of working postures	Sony Alpha A7R IV

Table 1 lists the main equipment used in this experiment and its purpose, covering seven aspects: joint angle, posture monitoring, movement trajectory recording, muscle loading measurement, equipment vibration monitoring, force data recording, and working posture analysis. The Vicon Vantage 3D motion capture system accurately records the trajectory of the worker’s movement; the Noraxon Ultium EMG analyzer is used to measure muscle loading and fatigue; the Brüel & Kjær vibration meter monitors the effects of equipment vibration on the worker’s upper limbs; the Tekscan FlexiForce load cell captures the force applied by the worker as he pushes the bracket and lifts the equipment; and the Sony Alpha A7R IV HD video camera is used to record working postures for subsequent movement analysis and biomechanical optimisation assessment. The combination of these devices enables a comprehensive and accurate analysis of biomechanics in coal mining operations. This experiment supports biomechanical optimisation by analyzing worker workloads through accurate data collection.

5.2. Experimental programme design

This experiment was conducted to analyze the biomechanical loads in general excavation and general mining operations and to assess the effectiveness of optimisation measures. The experiment was conducted in a simulated coal mine operating environment, and a standard operating group (current operating mode) and an optimized operating group (using biomechanically optimized solutions) were selected to compare the joint loads, muscle fatigue, vibration effects, and operating efficiencies under different operating modes.

The experiment includes two parts: the comprehensive excavation operation experiment and the comprehensive mining operation experiment. In the comprehensive excavation operation experiment, the subjects respectively carried out the operation of the comprehensive excavator, support handling, equipment maintenance, and other operations, wearing biomechanical monitoring equipment to record the joint angle, using electromyography (EMG) analysis to measure muscle fatigue, and using the vibration meter to monitor the vibration of the handle of the comprehensive excavator on the upper limb. In the experiments of comprehensive mining operations, the main hydraulic stent pushing, coal mining machine operation, conveyor maintenance, and other operations, the use of a three-dimensional motion capture system to analyze the movement trajectory and the combination of load sensors to measure the force during stent pushing and heavy lifting.

MATLAB R2023b (The MathWorks Inc., USA) and Biomechanics Analysis Pro v4.2 (BiomechSoft Inc., Germany) were used for data processing. MATLAB was employed for the development of custom scripts to perform inverse dynamics calculations, Fourier transform-based EMG frequency analysis, and joint load estimation. The scripts utilized the Signal Processing Toolbox for EMG signal denoising and frequency domain conversion, as well as the Statistics and Machine Learning Toolbox for variance analysis, hypothesis testing, and regression analysis of operational trends.

Biomechanics Analysis Pro v4.2 was used for motion trajectory modelling and muscle stress visualization. These combined software platforms enabled a comprehensive analysis of the workers' postural loads, fatigue levels, and vibration exposure, providing the data foundation for assessing the effectiveness of the biomechanical optimisation strategy.

5.3. Data collection and analysis methods

This experiment adopts biomechanical monitoring, motion capture, EMG analysis, and vibration testing to systematically collect human load data in the comprehensive excavation and mining operation and analyze the effects of operating posture on joints and muscles through calculation.

For data collection, the Xsens MVN biomechanical monitoring device was used throughout the experiment to record the workers' joint angles and postural changes, and the Vicon Vantage 3D motion capture system was used to track the movement trajectories and obtain the postural stability and movement patterns of the workers during operation. The Noraxon Ultium Electromyography (EMG) analyzer was used to measure the activity intensity of major muscle groups, quantify muscle load and fatigue levels, and detect the effects of equipment vibration on the nerves and muscles of the upper limbs using the Brüel & Kjær Vibration Meter. The Tekscan FlexiForce Load Sensor was used to measure the force exerted by the workers when they pushed the brackets and handled the equipment. The Tekscan FlexiForce load sensor is used to measure the forces applied by workers when pushing stands and handling equipment and is combined with a Sony Alpha A7R IV HD camera to capture video of the job and aid data analysis.

For data analysis, kinematic and kinetic analyses were performed using MATLAB R2023b and Biomechanics Analysis Pro v4.2 software to calculate joint shear forces, muscle stress distribution and fatigue trends. A custom MATLAB script was developed to process time-series EMG signals, implement inverse dynamics equations, and calculate shear force based on human mechanical load models. The script used built-in functions from the Signal Processing Toolbox and Statistics and Machine Learning Toolbox for noise filtering, feature extraction, and statistical analysis.

Statistical tests were conducted to assess the significance of differences between the standard and optimized operation groups. Paired two-tailed t-tests were used to compare joint shear forces and fatigue indices, while one-way ANOVA was employed to assess differences across multiple task categories. A significance level of $p < 0.05$ was adopted. All numerical results were reported with mean ± standard deviation, and 95% confidence intervals were calculated where applicable. These statistical methods ensured that the effectiveness of the optimisation measures was robustly supported.

5.4. Analysis of experimental results

The joint shear force of workers in general excavation and mining operations is one of the most important indicators of operational safety. Excessive shear force can lead to long-term damage to the lumbar spine and knee joints, increasing the risk of occupational diseases. This experiment measured the joint shear force under different operation modes, and the results showed that the shear force of the optimized operation group was significantly reduced, among which the shear force of the operation of the comprehensive excavator and the support and handling operation was reduced by the largest amount, by 24% and 22%, respectively, indicating that the optimized operation mode effectively reduced the joint load. Details are shown in **Table 2**.

Table 2. Joint shear measurements.

Type of operation	Standard operating group shear (N)	Optimised working group shear (N)	Shear force reduction (%)
Operation of IMDGs	2500	1900	24
Support handling	2700	2100	22
Equipment Maintenance	2600	2000	23
Hydraulic Bracket Pushover	2800	2200	21
Coal miner operation	2900	2300	21
Conveyor Maintenance	2750	2150	22

The data in **Table 1** shows that the average reduction of joint shear force in the optimized operation group is 22.2%, which effectively relieves the burden on workers' lumbar vertebrae and knee joints in the comprehensive excavation and comprehensive mining operations. The shear force in the operation of the heald digging machine is reduced from 2500 N to 1900 N, a reduction of 600 N, a decrease of 24%, and the optimisation effect is the most obvious. This indicates that the optimized height adjustment of the operating table and the optimized angle of the handle enable the workers to operate in a more biomechanical posture, thus reducing the lumbar spine force. The shear force of support handling decreased from 2700 N to 2100 N, a reduction of 600 N, or 22%, indicating that the optimized operating tools and handling posture adjustment effectively reduced the worker load. The shear force of hydraulic support pushing and coal mining machine operation decreased by 600 N and 21% respectively, indicating that the optimized electro-hydraulic boosting device and operation auxiliary equipment reduced the pressure on workers' lumbar vertebrae. The shear force for conveyor maintenance was reduced by 22% from 2750 N to 2150 N, indicating that the optimized handling tools and postural adjustments reduced the burden on the lower limbs. Overall, the optimised operation significantly reduced shear forces across all operation types, improving operational safety and reducing the risk of musculoskeletal injuries.

Prolonged high workloads can lead to the accumulation of muscle fatigue, reduce operational efficiency, and increase the risk of musculoskeletal injuries. In this experiment, electromyography (EMG) was used to measure the fatigue indices of the major muscle groups under different operating modes and to compare the muscle loading before and after optimisation. The details are shown in **Table 3**.

Table 3. Comparison of muscle fatigue.

Muscle group	Standard operating group fatigue index (%)	Fatigue index of optimised work groups (%)
Erector spinae muscle (anatomy)	65	45
Bicipital muscle	70	50
Deltoid muscle (over the shoulder)	68	48
Thigh muscles	60	42

As analyzed in **Table 2**, the fatigue indices of the optimized working group were lower than those of the standard working group for all major muscle groups, especially the fatigue indices of the erector spinae and quadriceps muscles, which decreased from 65% to 45% and 60% to 42% respectively, both of which were reduced by 30%. This indicates that the optimised work posture adjustment, lumbar support equipment, and bench height improvement effectively reduced the fatigue accumulation of lumbar and lower limb muscles and reduced the chronic strain injury caused by long-term bending and squatting work. The fatigue indices of biceps and deltoid muscles were reduced by 29%, from 70% to 50% and 68% to 48%, respectively, indicating that the optimised design of the equipment handles, the adjustment of the working height, and the weight distribution strategy significantly reduced the fatigue load of the upper limb muscles and improved the stability and durability of the workers' work.

Table 4. Comparison of equipment vibration impact.

Appliances	Standard operating group vibration (m/s^2)	Optimisation of work group vibration (m/s^2)	Vibration reduction (%)
Hybrid digger	12.5	8.2	34
Coal miner	15.2	9.8	36
Conveyors	14.8	9.4	36

Coal mining operations involve the operation of a large number of mechanical equipment, and equipment vibration has a significant impact on workers' health, and long-term exposure may lead to carpal tunnel syndrome, nerve damage and muscle fatigue. This experiment measured the vibration intensity when workers were exposed to the equipment under different operation modes. The details are shown in **Table 4**.

According to the analysis in **Table 3**, the vibration impact of the optimised operation group is reduced in all equipment operation sessions, among which the vibration of the coal mining machine is reduced from 15.2 m/s^2 to 9.8 m/s^2, a reduction of 36%, indicating that the use of polymer elastic vibration isolation material and hydraulic damping structure effectively reduces the vibration transmission and reduces the risk of worker's upper limb fatigue and vibration disease. The vibration of the conveyor was reduced from 14.8 m/s^2 to 9.4 m/s^2, a reduction of 36%, indicating that the optimised design of vibration-damping and vibration-isolating handles of the equipment foundation effectively mitigated the impact of prolonged operation on the arms of the workers. The vibration of the IMD machine decreased from 12.5 m/s^2 to 8.2 m/s^2, a reduction of 34%, indicating that the optimised handle structure and improved operating platform reduced the vibration load on the wrist and arm.

The optimised operation method enhances the workers' operational safety and improves the operational efficiency. This experiment compares the time required to complete the same task under different operating methods, and the results show that the operating time of the optimised operating group is 17%–23% shorter than that of the standard operating group, which indicates that the optimised biomechanical design, the adjustment of the operating process, and the improvement of the auxiliary equipment effectively improve the working efficiency and reduce the problem of work slowdown caused by fatigue. The details are shown in **Table 5**.

Table 5. Comparison of operational efficiency.

Type of operation	Standard operating group time (min)	Optimisation of workgroup time (min)	Efficiency gains (%)
Operation of IMDGs	35	28	20
Support handling	40	32	20
Equipment Maintenance	38	31	18
Hydraulic bracket pushover	42	35	17
Coal miner operation	45	36	20
Conveyor Maintenance	39	30	23

Combined with the analysis in **Table 4**, the average operating time of the optimised operation group is reduced by 19.7%, showing efficiency improvement in all operation segments, especially the conveyor maintenance time, which is shortened from 39 min to 30 min, with an efficiency improvement of 23%, indicating that the optimised handling auxiliary equipment and operation flow can significantly reduce unnecessary repetitive movements of workers and improve the work fluency. The operating time for the operation of the excavator, support handling, and coal mining machine was reduced by 20%, indicating that the optimised height adjustment of the operating table, handle design, and automated auxiliary equipment reduced the physical load on the workers and made the operation more efficient. The hydraulic support pushing operation time was shortened from 42 min to 35 min, with an efficiency improvement of 17%, indicating that the adoption of the electro-hydraulic boosting system and improved support pushing method effectively reduced the delay in the operation process. Overall, the optimised solution not only improves the physical load of the workers but also significantly improves the operation efficiency, which makes the coal mine comprehensive excavation and mining operation safer and more efficient [16].

5.5. Discussion and analysis of results

The experimental results show that the optimised biomechanical design has achieved significant results in reducing the workers' joint loads, reducing muscle fatigue, reducing the impact of equipment vibration and improving operational efficiency. In terms of joint shear force, the lumbar spine and knee joint shear force of the optimised operation group was reduced by 22.2% on average, of which the shear force of the IMC operation was reduced by 600N, down by 24%, indicating that the optimised height adjustment of the operating table and optimisation of the angle of the handles significantly reduced the burden on the waist of the workers.

In terms of muscle fatigue, the fatigue index of the erector spinae and quadriceps of the optimised work group decreased by 30%, indicating that the work posture adjustment, lumbar support equipment and knee aids were effective in reducing muscle fatigue. The upper limb muscle fatigue index decreased by 29%, indicating that the improved handle design and handling aids reduced the load on the upper limbs and improved worker endurance. Details are shown in **Figure 5**.

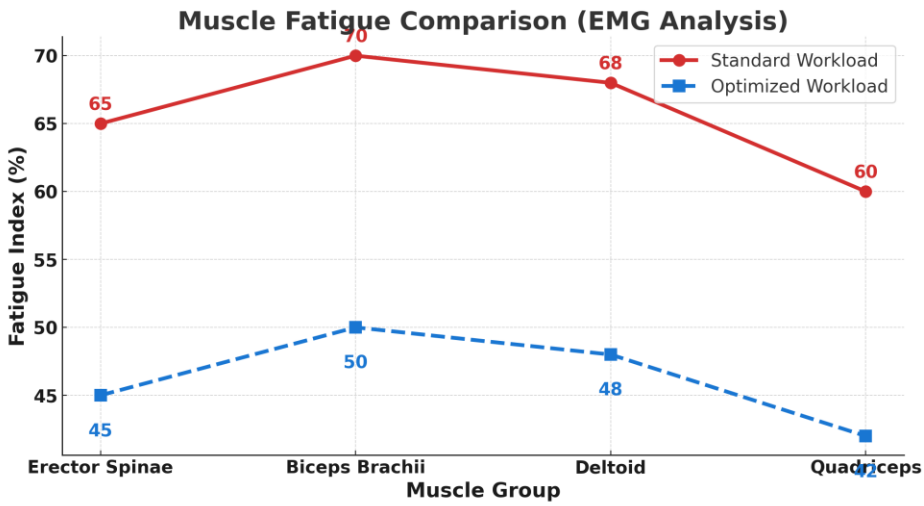

Figure 5. Comparison of muscle fatigue.

Regarding the impact of equipment vibration, the vibration of the equipment in the optimised operation group was reduced by 35% on average, especially the vibration of the coal mining machine decreased by 36%, indicating that the use of polymer vibration isolation materials and hydraulic damping handles significantly reduces the impact of vibration on the nerves and muscles of the arm and reduces the risk of vibration sickness caused by long-term operation. See **Figure 6** for details.

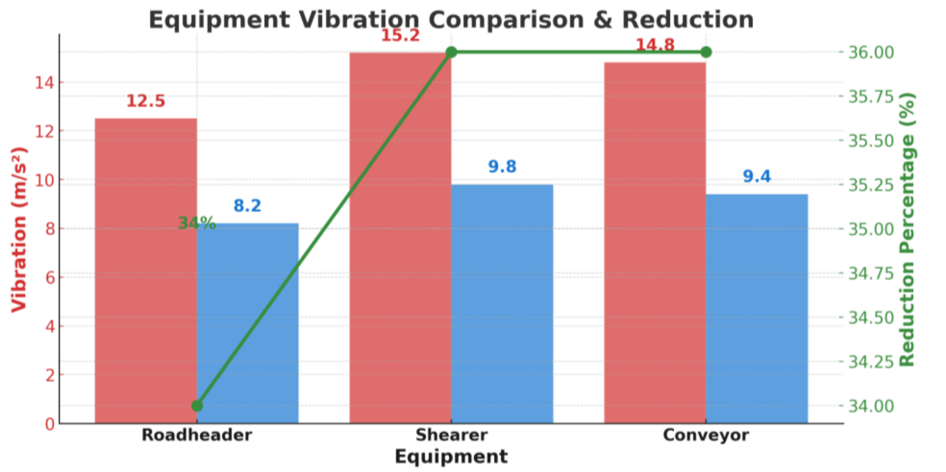

Figure 6. Comparison of equipment vibration impact.

In terms of operating efficiency, the average operating time of the optimised operation group is reduced by 19.7%, with the most obvious efficiency improvement of 23% in conveyor maintenance, indicating that the optimised mechanical auxiliary equipment and the rationalized operation process can effectively improve work fluency, reduce repetitive labor, and enable workers to complete the same workload with less physical exertion. See **Figure 7** for details.

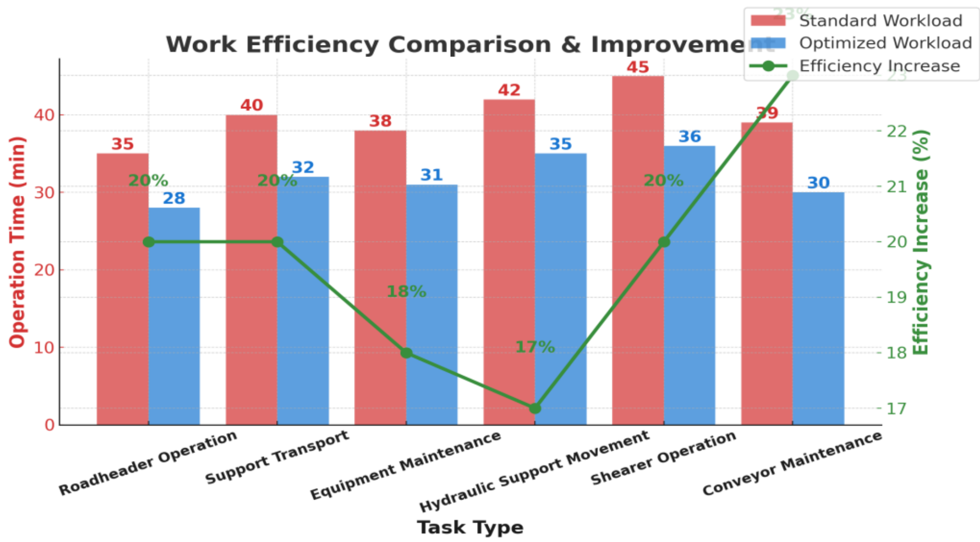

Figure 7. Comparison of operating efficiency.

Taken together, the optimised solution not only enhances operational safety but also improves work efficiency and reduces the risk of occupational diseases. In the future, it can be combined with intelligent sensing technology and an artificial intelligence analysis system to further optimize the operation posture monitoring and adjustment strategy to ensure the long-term safe and efficient operation of coal mine operations.

6. Conclusion

This study focuses on the biomechanical optimisation of comprehensive excavation and mining operations, through experiments to analyze the mechanism of different operating modes on workers' joint shear force, muscle fatigue, equipment vibration, and operating efficiency, and to verify the effectiveness of the optimisation design in improving the safety and efficiency of operations. The experimental results show that the optimised operation mode can significantly reduce the joint shear force and muscle fatigue, reduce equipment vibration, and improve the operation efficiency, which has strong engineering application value. In the future, the research should be combined with intelligent sensing technology to further optimize the real-time biomechanical monitoring system, achieve dynamic adjustment of operating parameters, and improve the ability of individualized operation optimisation. Focusing on the impact of long-term load in the complex operating environment of coal mines, the biomechanical risk prediction model should be established, and the applicability of operation optimisation under different working conditions should be explored in depth so as to provide theoretical support and technological guarantee for the development of the intelligent and precise safety protection system of coal mine operation.

Despite the promising findings, this study has several limitations. First, the sample size was limited to 30 participants, all from similar mining backgrounds, which may not fully represent the diversity of physical characteristics and task variations across the wider mining workforce. Second, the experiments were conducted in a simulated coal mine environment, which, although designed to replicate real conditions, could not completely reproduce the complex factors of actual mining sites, such as dust concentration, temperature variation, and spontaneous task switching. Furthermore, the short-term nature of the trials did not capture the cumulative biomechanical effects of long-term repetitive operations. Future research should involve larger-scale, multi-site studies with longer observation periods and real-time field deployment to verify and expand the applicability of the findings.

Ethical approval: Not applicable.

Informed consent statement: Not applicable.

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