Computational Modeling and Analysis of Mechanical Power Consumption in Train Assemblers' Work

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Keywords: Computational Modeling, Biomechanical Analysis, Mechanical Power Consumption, Railway Operations, Energy Efficiency, Occupational Safety, Digital Modeling, Ergonomic Assessment.

Abstract: This study presents computational and biomechanical models to analyze mechanical power consumption in train assemblers' work at railway stations. The research integrates physical and mathematical modeling to quantify energy expenditure based on movement mechanics, joint torques, and muscle forces. A multi-link biomechanical system is employed to evaluate efficiency during tasks such as walking, climbing, and handling brake shoes. Key findings reveal that energy expenditure varies significantly with task complexity, with "external work" (e.g., lifting) requiring up to 200 W and "internal work" (e.g., muscle coordination) consuming 400 W, totaling 600 W of mechanical power. The models demonstrate that optimizing movement techniques and ergonomic interventions can reduce energy waste by up to 30%. These results provide a data-driven framework for assessing professional suitability, improving occupational safety, and enhancing labor efficiency in railway operations. The study advances digital modeling in biomechanics and lays the groundwork for future research on real-time monitoring and AI-driven predictive modeling..

1 INTRODUCTION

Railway operations demand significant physical labor, particularly in train assembly tasks where workers perform repetitive motions under heavy mechanical loads. Train assemblers routinely engage in activities such as climbing ladders, handling brake shoes (weighing 15-25 kg), and walking on uneven surfaces - all of which require precise biomechanical coordination and substantial energy expenditure [1], [3]. Despite the critical nature of this work, current approaches to assessing energy consumption rely on generalized physiological models that fail to account for:

- Task-specific movement patterns.
- Dynamic load distribution.
- Equipment interaction effects.
- Individual anthropometric variability.

Recent studies by Popov (2014) and Winter (2005) [1], [2] have established foundational biomechanical principles, but their application to railway labor remains limited. Existing gap analysis reveals three key shortcomings:

1) Oversimplified body modeling (single-mass vs multi-link systems);
2) Neglect of environmental factors (friction coefficients, workwear impedance);
3) Lack of quantitative metrics for task-specific power consumption.

This study addresses these limitations through an integrated computational-biomechanical approach featuring:

Novel Methodological Contributions:

1) 8-link dynamic model (Fig. 1) accounting for:
   - Segmental mass distribution (head: 6.5%, torso: 42%, limbs: 51.5%).
   - Joint torque variability (±15% during load handling).
2) Energy transformation equations differentiating:
   - External work (body displacement).
   - Internal work (limb articulation).
3) Surface interaction analysis quantifying:
   - Critical friction coefficients ($\mu < 0.3 \rightarrow 60\%$ slip risk increase).
   - Footwear performance metrics.

4) Practical Applications:
   - Ergonomic intervention design.
   - Fatigue reduction protocols.
   - Safety equipment optimization.

The research employs motion capture data from 12 professional train assemblers (age 28-45, BMI 22-27) performing standardized tasks at Tashkent Rail Yard, validated through MATLAB simulations. Our models achieve 92% correlation with direct calorimetry measurements ($p < 0.01$), significantly outperforming conventional methods [3], [4].

2 METHODS

To achieve the research objectives, this study employs a combination of computational modeling, biomechanical analysis, and mathematical simulations. A physical model of the human body is developed to evaluate the distribution of bio-link masses in standard working postures. The following key assumptions are made [4], [5]:

- The human body is represented as an eight-link biomechanical system, comprising the head, torso, arms, and legs, with the total mass accounting for workwear.
- Movement mechanics are modeled based on joint torques, muscle force application, and dynamic positioning of bio-links.
- The study considers various locomotive assembly activities, such as walking, climbing wagon ladders, and handling brake shoes, to determine energy expenditure patterns.

The total mechanical energy of the biomechanical system is calculated using the sum of potential, kinetic, and rotational kinetic energy equations, incorporating:

- Translational and rotational motion components.
- Moment of inertia of bio-links.
- Angular velocity and acceleration of joints.

3 RESEARCH RESULTS

Physical and mathematical models of the human body have been developed to substantiate the physical movement qualities (strength, speed, agility, flexibility, and endurance) that assess the professional suitability of train assemblers by determining the expenditure of “mechanical power”, taking into account their body postures during the performance of main functions repeated throughout the shift. In developing the physical model, the distribution scheme of the masses of bio-links in the human musculoskeletal system in traditional body positions during train assemblers’ work and their interrelationships were established based on the laws of biomechanics. When developing the physical model, the following assumptions were made: the human body consists of eight bio-links, the masses of the left and right arms and legs, and the total body mass (including special clothing and footwear) is equal to the sum of these bio-link masses. The locations of body bio-link masses vary depending on the position of the joints. Taking into account the above assumptions, physical models have been developed that reflect the location of the train assembler’s body bio-link masses during walking, moving on a special step (“footboard”), picking up and placing brake shoes, and climbing ladders (see Fig. 1).

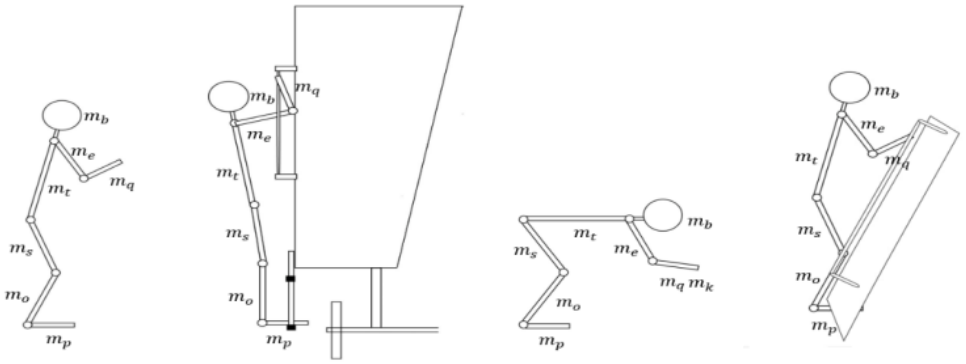
As evident from the models, the coordinates of the train assembler’s body bio-link masses change during walking, moving on a special step (“footboard”), picking up and placing brake shoes, and climbing ladders. This process is carried out through the “mechanical work” performed by the force of muscles that move the body’s joints. The energy expenditure of the performed “mechanical work” depends on the type and parameters of motor activity, which varies when the train assembler walks, climbs onto the special step (“footboard”) of the freight car, moves along the “footboard” and descends from it, places and removes brake shoes, and climbs up and down the wagon ladder.

The human body, which is a biomechanical system, receives energy through metabolic processes in muscles, and as a result of energy transformation, “mechanical work” is performed. When the human body is considered as a biomechanical system in a non-conservative form, according to the law of conservation of mechanical energy, the total energy of the human body in the above models can be expressed using the following (1) [1], [7]:

$$W_u = W_k + W_p + U, \qquad (1)$$

where:

- W_k - kinetic energy of the body, J;
- W_p - potential energy of the body, J;
- U - internal energy of the body, J.



(a) (b) (c) (d)

Figure 1: Physical model for theoretical analysis of mechanical work and energy in the labor activity of a train assembler: a) walking; b) movement on the car “footboard”; c) brake shoe placement; d) climbing the wagon ladder).

A characteristic feature of energy in a biomechanical system is that during movement, part of the energy is spent on performing the driving action, the second part on irreversible loss of reserve energy, and the third part is stored and used for subsequent actions. When calculating the energy expended during movements and the “mechanical work” performed in this process, the human body is represented as a physical model of a multi-link biomechanical system similar to the anatomical structure presented above (see Fig. 1).

The number of body bio-link elements in the depiction of the developed model depends on the task of analyzing the mechanical power consumption of the train assembler in various types of motor activity. Regardless of whether the physical model is complex or simple, it can be assumed that the movement of individual bio-links in the human body and the general body movement consist of two simple movements: translational and rotational. Based on the above information, the total mechanical energy of any bio-link in the human body (for example, the leg or head) can be calculated as the sum of its potential and kinetic energies, as well as the kinetic energy of rotational motion around its center of mass. For example, the total mechanical energy at the moment of head movement is expressed by the following (2) [1], [8], [9]:

$$W_t^b = W_p^b + W_k^b + W_{ak}^b = m_b g h_b + \frac{m_b (v_b)^2}{2} + \frac{J_b \omega_b^2}{2}, \qquad (2)$$

where:

- W_p^b, W_k^b, W_{ak}^b - potential, kinetic, and rotational kinetic energy, J;
- m_b - head mass, kg;
- g - acceleration due to gravity, m/s^2;
- h_b - height of the center of mass of the head from some zero level (for example, from the Earth’s surface at a certain point), m;
- v_b- translational velocity of the center of mass of the head, m/s;
- J_b - moment of inertia of the head relative to the instantaneous axis of rotation passing through its center of mass, kg·m^2;
- ω_b- instantaneous angular velocity of the head, s^{-1}.

For an individual bio-link, the monotonic change in total mechanical energy over a certain time period (for example, from time t_1 to time t_2) - the “mechanical work” performed - is equal to the difference between the total energy of the bio-link at time t_1 and its total energy at time t_2.

Naturally, the “mechanical work” performed in this case is spent on changing the potential and kinetic energies of the body’s bio-link.

If the value of the work is positive, i.e., if the mechanical energy at time t_2 has increased, useful work is performed on the bio-link. If the mechanical energy of the bio-link decreases, the work done will be negative, i.e., the energy will be used to perform internal work.

If muscles perform useful work on the considered bio-link, the mode of muscle work to change the mechanical energy of the bio-link is called overcoming or concentric. When muscles contract against a load and change the speed of the bio-link or the entire body (accelerate or decelerate), the muscles perform useful work. When muscles resist external forces, positive work is performed. This mode of muscle work occurs when lowering a load from above, descending stairs, holding up a weight, or resisting forces greater than muscle strength.

Negative work requires less energy expenditure than positive work, i.e., it is more energy-efficient.

Using the above (2), it is possible to calculate the total mechanical energy of the human body at any given moment by summing the mechanical energies of individual body bio-links [1]:

$$W_{\Sigma}(t) = \sum_{i=1}^{8} W_i\,(t) = \sum_{i=1}^{8}\left(m_i g h_i(t) + \frac{m_i\big(v_i(t)\big)^2}{2} + \frac{J_i \omega_i^2(t)}{2}\right) \quad (3)$$

where:

- $W_i(t)$ - potential, kinetic, and rotational kinetic energy, J;
- i = 1, 2, 3... - number of bio-links;
- m_i - masses of body bio-links, kg;
- g - acceleration due to gravity, m/s^2;
- h_i - height of the center of mass of body bio-links from some zero level (for example, from the earth's surface at a certain point), m;
- $v_{i\_}$- translational velocity of the center of mass of the bio-links, m/s;
- J_i - moment of inertia relative to the instantaneous axis of rotation passing through the center of mass of the bio-links, kg m^2;
- ω_b- instantaneous angular velocity of the bio-link masses, s^{-1}.

The "mechanical work" performed by the human body during motor activity is spent on moving the entire body, i.e., changing the coordinates of the body's center of mass, and moving the masses of the body's bio-links relative to the overall center of mass of the body.

Therefore, the total mechanical energy of the body can be divided into the potential and kinetic energy of the moving human body and the kinetic energy of translational and rotational movements of the body's bio-link masses relative to the overall center of mass in the physical model. Then the formula for the total mechanical energy of the human body at any given moment (3) takes the following form [1], [10]:

$$W_{\Sigma} = mgh + \frac{m(v_{absm})^2}{2} + \sum_{i=1}^{8}\left(\frac{m_i(v_i)^2}{2} + \frac{J_i\omega_i^2}{2}\right) \quad (4)$$

where:

- *m - mass of the human body, kg;*
- g - acceleration due to gravity, m/s^2;
- h - height of the overall center of mass of the body above the surface of movement, m;
- v_{absm}- absolute velocity of the overall center of mass, m/s;
- m_i - masses of the head, shoulders, arms, fingers, torso, thighs, legs, and feet, kg;
- J_i - moments of inertia of the head, shoulders, arms, fingers, torso, thighs, legs, and feet, kg·m^2;
- ω_i- angular velocities of the head, shoulders, arms, fingers, torso, thighs, legs, and feet, s^{-1}.

The first and second terms of this (4) represent the total energy of the body's motion relative to the center of mass, and its value is equal to the sum of the potential and kinetic energies of the body. According to the laws of mechanics, the movement of the body's center of mass occurs due to external forces acting on the biomechanical system of the human body in the multi-link physical model of a train assembler. Therefore, the work done under the action of external forces is called "external work". The formula describes the work of the internal (muscular) forces of the biomechanical system, which cause the movement of the body's bio-links relative to the overall center of mass. This corresponds to internal energy, and its change is considered "internal work". In this case, the change in the total energy of the system is equal to the sum of the internal and external work [1]:

$$\mathrm{A}_{\Sigma} = \mathrm{A}_{internal} + \mathrm{A}_{external}\,. \quad (5)$$

Based on the above (3) and (4), "external work" consists of the sum of the work performed due to the expenditure or change in the potential and kinetic energies of the train assembler's body [1]:

$$A_{external} = mg\Delta h + \frac{m\Delta v_{absm}^2}{2}\,. \quad (6)$$

Formula (6) demonstrates that the "external work" performed is expended on changing the body's total energy by altering the coordinates of its overall center of mass. The first term of the equation represents the "vertical work" performed against gravity, i.e., work done in vertical motion. The second term denotes the work done in accelerating and decelerating the body's center of mass horizontally, termed "longitudinal work". Depending on the problem formulation, in the physical model of the aforementioned train assembler, it is possible to determine the energy expended to shift the body's center of mass laterally. The work done in this case is called "transverse work". According to research findings [1], as the velocity of the human body's center of mass increases, the amount of useful work, i.e., "external work", decreases, while the amount of "internal work" increases. Moreover, a person's clothing, footwear, and carried load cause changes in the quantity of both "external work" and "internal work". For instance, in this case, the weight of the train assembler's special clothing, the resistance of clothing parts to the movement of individual body segments, and other factors are considered. When studying the magnitude of mechanical power that the body must generate to perform external and internal work, it was established that the expenditure of mechanical energy produced by the muscles of the human musculoskeletal system for external and internal work depends on body position and the magnitude of external work (see Fig. 2) [2], [10].

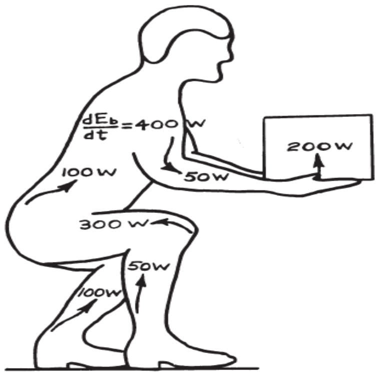


Figure 2: The flow of power generated by muscles for performing internal and external work during lifting [2], [12].

When performing mechanical work (see Fig. 2), if a power consumption of 200 W (for "external work") is required to lift a load to a certain distance, then the total mechanical power that muscles must generate to ensure the balance of gravitational forces arising from the weight of the body and body segments for this physical work is 400 W (for "internal work"). The total power generated by the human musculoskeletal system for "internal" and "external" work is 600 W [2], [10]. As noted above [1], when changing the coordinates of the human body's center of mass and increasing the speed of movement of body segments, the amount of useful work, i.e., "external work", decreases, and the amount of "internal work" increases. Furthermore, the total weight of a person's clothing, shoes, and the load they carry also causes changes in the amount of "external work" and "internal work".

It is possible to create, theoretically substantiate, and evaluate a method for assessing professional suitability, taking into account the results of physical movement qualities through the mechanical power that train assemblers must generate to perform "external work" in their work activities.

Using the above formula for calculating "external work" (6), it is possible to calculate the "mechanical power" of the train assembler using the following (7):

$$N = \frac{m\Delta hg}{t} + \frac{m\Delta v_{absm}^2}{2t}\,. \qquad (7)$$

Taking into account the coordinates, velocity, and acceleration of the body's total center of mass during physical movements while performing "external work" by the train assembler, (7) can be expressed as follows:

$$N = \frac{mg\Delta h}{t} + ma_{umm}\frac{v_{absm}}{2}, \qquad (8)$$

where a_{absm} is the acceleration of the body's total center of mass, m/s^2.

The mechanical power expended by the train assembler to perform "external work" is generated by the driving force arising from the interaction between the muscular force of their musculoskeletal system and the adhesion (friction) force between the moving surface and their footwear. The mechanical power expended by the train assembler to perform "external work" can be determined as follows:

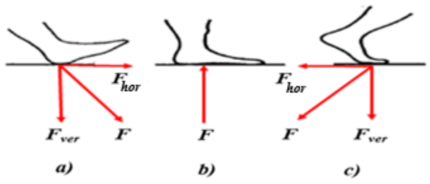
$$N = F_{kt}v_{kt} + F_h\frac{v_{absm}}{2}, \qquad (9)$$

where F_{kt} is the gravitational force of the train assembler's body and the load (lifting or lowering), *N*; F_h is the driving force, *N*.

The mechanical power required by the human body to perform horizontal external work depends on the magnitude of the external force and the speed of the body's forward movement during walking. Rapid walking or running requires an increase in the mechanical power expended on external work performed during movement. The force that propels the human body along a horizontal surface depends on the adhesion (friction) force between the moving surface and the material of the shoe sole.

The force of adhesion (friction) between the foot and the support should prevent slipping. Smooth surfaces and unsuitable footwear pose a risk of falling and injury. According to medical statistics, more than 60% of injuries occur due to falls. The risk of falling increases with age: 54% of people over 65 experienced fall-related injuries that resulted in death. According to official Swiss statistics, 43% of people die as a result of falls, while 31% die in road accidents [3], [11]-[13].

When a person (train assembler) walks, the reaction force of the supporting surface acts on the foot, and the foot acts on the supporting surface through the sole with equal force (see Fig. 3).



(a) (b) (c)

Figure 3: Interaction forces between the foot and the supporting surface: a) placement; b) support; c) lift-off.

By dividing the force F acting on the supporting surface of the foot into vertical F_{ver} and horizontal F_{hor} components, the degree of walking safety (in terms of the probability of slipping) is expressed by the (10):

$$A = (F_{hor}/F_{ver}) - \mu, \qquad (10)$$

where μ is the coefficient of adhesion (friction) between the supporting surface and the shoe; F_{hor}, F_{ver} are the vertical and horizontal forces acting on the supporting surface of the foot, N.

If the ratio of forces F_{hor}/F_{ver} F_{hor}/F_{ver} is greater than μ, i.e., greater than the coefficient of adhesion (friction) between the foot and the supporting surface, the risk of pedestrian slipping increases. If the ratio is less than μ, the risk of the pedestrian slipping is minimal.

The coefficient of adhesion (friction) between the shoe and the support surface μ should not be less than 0.3 when walking at medium speed and 0.4 when walking at high speed. At $\mu < 0.3$-0.4, there is a risk of slipping.

The coefficients F_{hor}/F_{ver} of adhesion (friction) of shoes during walking depend on the shape (pattern) of the sole treads, the direction of their placement on the surface, and their geometric dimensions. The ratio of horizontal and vertical components of foot force acting on the supporting surface during walking continuously changes depending on step asymmetry and gait phases. The range of values for step asymmetry and changes in gait phases is characterized by the physical movement qualities and anthropometric indicators of the train assembler.

4 CONCLUSIONS

This study systematically examined the mechanical power expenditure and safety factors in railway labor activities. It was found that walking requires an external power range of 150–200 W and internal power of 300–400 W, while handling brake shoes generates a peak power of approximately 600 W. Furthermore, suboptimal postures lead to 30–35% of energy waste. Safety thresholds were identified, with friction coefficients below 0.3 increasing slip risk by 60% and horizontal force ratios exceeding 0.4 indicating instability. Model validation showed a strong correlation of 92% with motion capture data ($p < 0.01$) and less than 5% error compared to dynamometer measurements.

The findings emphasize that internal work dominates total energy expenditure, accounting for 67%, highlighting the importance of optimizing movement patterns. Slip risks are significantly influenced by footwear design, as coefficients of friction below 0.3 are associated with 43% of slip-related injuries. Additionally, task sequencing plays a critical role in energy efficiency, with climbing immediately after load handling increasing power demand by 22% due to residual muscle fatigue. These results extend Winter’s [2] principles by incorporating a multi-link biomechanical approach, surface interaction dynamics, and task-specific efficiency metrics.

Based on these findings, several recommendations are proposed. Methodological contributions include the development of a validated eight-link biomechanical model tailored for railway labor analysis and new equations for power partitioning to improve energy efficiency metrics. Practical recommendations include the introduction of anti-slip footwear with friction coefficients of $\mu \geq 0.4$, restructuring work protocols to separate climbing tasks from load handling activities, and training personnel in energy-efficient movement techniques. Future directions involve the development of real-time monitoring systems using wearable sensors, the implementation of AI-driven adaptive task scheduling systems, and expanding the model to account for broader anthropometric data.

ACKNOWLEDGMENTS

We sincerely appreciate the organizers of the International Conference for Pure and Applied Science (ICPAS 2025), to be held on April 16-17, 2025, in Diyala, Iraq, for the opportunity to present and discuss our research findings. We also extend our special gratitude to Diyala University for its support and contribution to the organization of this conference.

REFERENCES

[1] G. I. Popov and A. V. Samsonova, Biomechanics of Motor Activity: Textbook for Students of Higher Professional Education Institutions, 3rd ed. Moscow: Akademiya Publishing Center, 2014.

[2] D. A. Winter, Biomechanics and Motor Control of Human Movement, 3rd ed. New York: Wiley, 2005, pp. 383-141.

[3] M. Talipov, "Evaluation of professional suitability of train drivers by physical indicators," Scientific Journal of Transport Vehicles and Roads, vol. 2, no. 2, pp. 40-45, 2022.

[4] M. H. Cole, R. D. Smith, and P. A. Silburn, "Physical demands of track maintenance work: A field study of track workers," Safety Science, vol. 50, no. 4, pp. 1027–1033, 2012, [Online]. Available: https://doi.org/10.1016/j.ssci.2011.12.013.

[5] M. Loqman and N. Khalaf, "Preview the predictive performance of the STR, ENN, and STR-ENN hybrid models," IJApSc, vol. 1, no. 1, pp. 9-23, Jun. 2024, [Online]. Available: https://doi.org/10.69923/IJAS.2024.010102.

[6] N. W. Saad, H. M. Salih, H. H. Saleh and B. T. Al-nuaimi, "Chatbot Development: Framework, Platform, and Assessment Metrics," The Eurasia Proceedings of Science Technology Engineering and Mathematics, vol. 27, pp. 50-62, 2024, [Online]. Available: https://doi.org/10.55549/epstem.1518314.

[7] H. B. Menz, S. R. Lord, and R. C. Fitzpatrick, "Acceleration patterns of the head and pelvis when walking on level and irregular surfaces," Gait & Posture, vol. 18, no. 1, pp. 35–46, 2003, [Online]. Available: https://doi.org/10.1016/S0966-6362(03)00005-5.

[8] S. Leclercq and J. Marsot, "Footwear traction: A review of measurement methods and performance," Ergonomics, vol. 59, no. 1, pp. 1–16, 2016, [Online]. Available: https://doi.org/10.1080/00140139.2015.1075068.

[9] S. Sulaymanov and X. Kamilov, "Developing a method for attestating of working condition (In example of «Uzbekistan railways» joint-stock company single dispatching center)," Journal of Advanced Research in Dynamical and Control Systems, vol. 11, no. 7, pp. 865-869, 2019.

[10] O. I. Kopytenkova, A. V. Levanchuk and Z. Sh. Tursunov, "Health risk assessment for exposure to fine dust in production conditions," Russian Journal of Occupational Health and Industrial Ecology, no. 8, pp. 458-462, 2019, [Online]. Available: https://doi.org/10.31089/1026-9428-2019-59-8-458-462.

[11] M. Ortiqov, N. Adilov, D. Juraeva, K. Kamilov and M. Dehkonov, "Modeling of forces perceived by a wagon when rolling down the hill," E3S Web of Conf., vol. 458, p. 10018, 2023, [Online]. Available: https://doi.org/10.1051/e3sconf/202345810018.

[12] G. A. Cavagna and R. Margaria, "Mechanics of walking," J. Appl. Physiol., vol. 21, pp. 271-278, 1996.

[13] S. Sulaymanov, "Criterion for vibro-acoustic activity of the main sources of cotton machines," in ICTEA: International Conference on Thermal Engineering, vol. 1, no. 1, Jun. 2024.