Beyond Mechanical Work: Heat Loss in Energy Expenditure

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Summary

This study highlights the necessity of thermodynamic analysis that considers both mechanical work and heat loss for accurate understanding of metabolic energy expenditure (EE). Through experiments of isometric exercises and exercises with constant mechanical work, we confirmed that when the effect of heat loss is eliminated from EE, it aligns with mechanical work. Therefore, this study suggests that the nonlinear response and variability in EE, which cannot be explained by mechanical work alone, are closely related to heat loss.

Introduction

Previous studies have used mechanical work-based calculations as a simplified approach to estimate energy expenditure (EE), circumventing the need for complex apparatus such as respiratory gas analysis systems. However, muscular energy efficiency demonstrates variability contingent upon multiple parameters, including exercise modality and movement frequency [1], resulting in non-linear relationships between EE and mechanical work. The first law of thermodynamics establishes that EE can be expressed as the summation of joint mechanical work (W) and heat loss (Q) [2]. Notably, in conditions dominated by positive mechanical work, EE efficiency consistently approximates 20% [1]. These observations indicate substantial thermal dissipation of metabolic energy, underscoring the necessity for a comprehensive thermodynamic analysis that incorporates both mechanical work and heat loss components for precise quantification of metabolic EE.

Methods

This study considered isometric and constant mechanical work conditions where EE becomes independent of mechanical work. These experiment conditions were implemented through two types of exercises: seated cable row and sinusoidal arm movements, each performed by ten healthy male participants in their 20s. In the seated cable row, exercise loads were adjusted to 10%, 20%, and 30% of each set's one-repetition maximum (1RM) (Figure 1). For sinusoidal arm movements, while movement frequency and exercise load were varied, the total mechanical work was maintained constant across the three conditions (Figure 1). Additionally, using dampers, only positive mechanical work (W+) was generated. Each set consisted of 7 minutes of exercise followed by 15 minutes of rest. Heat flux sensors (Carela Research, greenTEG) were attached to upper body muscles to measure heat loss, and a metabolic system (K5, COSMED) was used to assess oxygen consumption and EE.

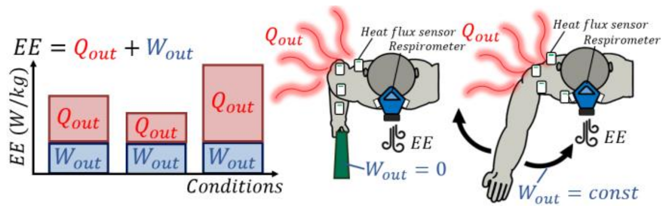

Figure 1: Thermodynamic analysis of metabolic EE (left) in isometric (center) and constant mechanical work (right) exercises.

Results and Discussion

The result illustrates the convergence between EE minus heat loss and measured W+ (Figure 2). These results indicate that both the nonlinear relationship between EE and mechanical work and the variability patterns in EE observed across different exercise loads and movement frequencies within each W+ condition are primarily driven by heat loss mechanisms. This phenomenon can be attributed to heat loss responses that operate independently of mechanical work, including activation-maintenance heat rate and the interactions between joint torque and velocity parameters [2].

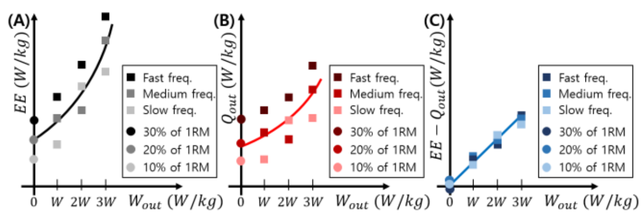

Figure 2: Pilot and anticipatory graphs of (A) EE, (B) Q_{out}, and (C) the difference between EE and Q_{out} for each W_{out} condition.

Conclusions

The nonlinear response and variability in EE, which could not be explained by mechanical work alone under identical W+ conditions, can be explained by considering heat loss. These findings confirm that a thermodynamic perspective is necessary for precise analysis and prediction of EE.

Acknowledgments

This study was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. N01240997).

References

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