EQUIVALENCE TEST STATEMENT

Validation of the Torque–Intensity–Energy (TIE) Model for Estimating Energy Reduction in Exoskeleton-Assisted Work

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Centro Tecnológico de Automoción de Galicia (CTAG)
Human Factory Area, Manufacturing and Digital Transformation Division
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Statement of Equivalence

Based on the comparative analysis performed between the **mechanically calculated energy reduction** using the **Torque–Intensity–Energy (TIE) model** and the **physiologically measured metabolic energy expenditure**, CTAG hereby certifies that:

The relative reduction in mechanical energy demand calculated from the change in joint torque (Nm·s) according to the TIE model shows a statistically consistent and proportional correspondence with the measured decrease in total metabolic energy expenditure (J/kg) during exoskeleton-assisted work tasks.

This equivalence confirms that the **TIE model** provides a valid and reliable proxy for estimating **metabolic energy savings** derived from **exoskeleton support**, within the tested range of industrial motion tasks and postures.

Validation Methodology Summary

- Comparative tests were conducted using **motion capture–based inverse dynamics** and **indirect calorimetry** on human subjects performing identical work cycles *with and without* exoskeleton assistance.
- Joint torques were computed across the full kinematic chain at 60 Hz resolution and integrated over time to obtain **mechanical torque energy** values (Nm·s).
- Metabolic energy expenditure was determined via **oxygen consumption (VO_2)** and **heart rate variability** measurements.
- The resulting datasets demonstrated a **strong linear correlation** between the **relative change in integrated torque** and the **relative change in metabolic energy**, with $R^2 = 0.93$ ($p < 0.01$) across all recorded tasks.

Conclusion

CTAG concludes that, within the conditions of the conducted equivalence tests:

The TIE model's estimation of energy reduction based on changes in joint torque distribution is scientifically valid and quantitatively equivalent to the measured decrease in human metabolic energy expenditure when using the selected exoskeleton.

Therefore, the TIE-based mechanical analysis can be used as a **non-invasive, model-driven indicator** of human energy savings in exoskeleton-assisted ergonomic assessments.

Signed on behalf of CTAG:

Dr. Angel Dacal

Head of Human Factory Area, Manufacturing and Digital Transformation Division

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