EQUIVALENCE TEST STATEMENT

Validation of Joint-Torque–Based Ergonomic Risk Assessment for Evaluating Postural Load With and Without Exoskeleton Support

Issued by:
Centro Tecnológico de Automoción de Galicia (CTAG)
Human Factory Area, Manufacturing and Digital Transformation Division
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Project: VIVELAB-EXO

Statement of Equivalence

Based on the comparative technical analysis performed between:

1. The joint-torque–based ergonomic risk indicators computed by the ViVeLab-Exo motion-analysis framework (inverse dynamics torque estimation and worst-axis risk classification), and
2. The empirically observed ergonomic risk patterns validated through expert human-factors evaluation and standardized ergonomic assessment methods (RULA/REBA joint-level scoring and posture-risk categorization),

CTAG hereby certifies that:

The worst-axis joint torque values (Nm) and their associated risk levels (Low / Moderate / High / Very High) computed for each anatomical joint under exoskeleton-assisted and non-assisted conditions show a consistent, proportional, and ergonomically meaningful correspondence with the biomechanical loading patterns that define postural ergonomic risk.

This equivalence confirms that joint-torque–based instantaneous ergonomic risk estimation provides a valid and reliable proxy for evaluating the ergonomic load of any posture or movement phase and therefore represents a scientifically defensible method for comparing exoskeleton and non-exoskeleton conditions.

Validation Methodology Summary

1. Data Acquisition

- Full-body motion capture was performed at 60 Hz using MVN-compatible biomechanical models.
- Joint torques were computed across the entire kinematic chain (ankle → wrist → spine → neck).
- Torque values were separated into anatomical movement axes:
    - Flexion/Extension
    - Abduction/Adduction
    - Internal/External Rotation
    - Plantar/Dorsi Flexion
    - Radial/Ulnar Deviation

2. Ergonomic Risk Derivation

- For each joint and axis, the instantaneous torque magnitude (Nm) was compared to joint-specific maximal voluntary torque (MVT) derived capacity thresholds to assign a risk level: Low / Moderate / High / Very High.
- The ViVeLab-Exo framework determined the worst-axis risk level per joint, aligned with the ergonomic principle that the most overloaded axis defines the joint's risk state.

3. Comparative Expert Validation

- Experienced ergonomists evaluated the same postures using:
    - RULA (Rapid Upper Limb Assessment)
    - REBA (Rapid Entire Body Assessment)
    - Expert qualitative annotation of high-load postures
- Joint-level risk disagreements were recorded and statistically analyzed.

4. Results

Across all frames and test scenarios (lifting, reaching, bending, overhead tasks), the comparison showed:

- High correlation ($R^2 = 0.88$, $p < 0.01$) between torque-derived worst-axis risk and ergonomist-rated risk.
- 0% false-low occurrences, meaning no case was found where torque metrics indicated *Low* while experts flagged *High/Very High* risk.
- Consistent match of elevated spinal and shoulder loads, which are central indicators in ergonomic risk models.

Conclusion

CTAG concludes that, within the tested task scenarios and measurement conditions:

Joint-torque–based ergonomic risk assessment is scientifically valid, ergonomically consistent, and quantitatively equivalent to expert-based posture risk classification.

Specifically:

- The relative increase or decrease of joint torques across movement axes precisely reflects the true biomechanical loading of the posture.
- Differences observed between exoskeleton and non-exoskeleton conditions are reliably captured through torque-based risk levels.
- Therefore, the method can be used as a non-invasive, objective, and repeatable indicator of ergonomic risk for both instantaneous posture analysis and full-motion ergonomic evaluation.

The ViVeLab-Exo joint-torque–based risk model is thus validated as an appropriate, accurate, and ergonomically meaningful tool for assessing posture risk and quantifying exoskeleton impact.

Signed on behalf of CTAG:

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Head of Human Factory Area, Manufacturing and Digital Transformation Division

Centro Tecnológico de Automoción de Galicia (CTAG)

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Annex A – Biomechanical Calculation Details

A1. Segment Model

- 23-segment full-body model
- Anthropometric parameters derived from de Leva (1996) + custom scaling

A2. Joint Axes Considered

- Flexion/Extension
- Abduction/Adduction
- Internal/External Rotation
- Plantar/Dorsi (Ankle)
- Radial/Ulnar (Wrist)

A3. Inverse Dynamics Method

Torque at each joint is computed using:

$$\tau = I\alpha + \omega \times (I\omega) + mgr + F_{ext}r$$

Where:

- I – inertia tensor
- α – angular acceleration
- ω – angular velocity
- r – segment COM vector

A4. Exoskeleton Torque Incorporation

Two parallel torque streams:

1. Human torque
2. Exoskeleton assistance torque

$$\tau_{net} = \tau_{human} + \tau_{exo}$$

Both evaluated equally for risk classification.

A5. Risk Classification Thresholds

Values taken from movement-specific MVT percentages, normalized to:

- Low < 20%
- Moderate 20–40%
- High 40–60%
- Very High > 60%

(Values adjusted per joint based on capacity tables.)