Energy Usage Measurement

The TIE (Torque–Intensity–Energy) Model

The human body's response to physical and mental stress

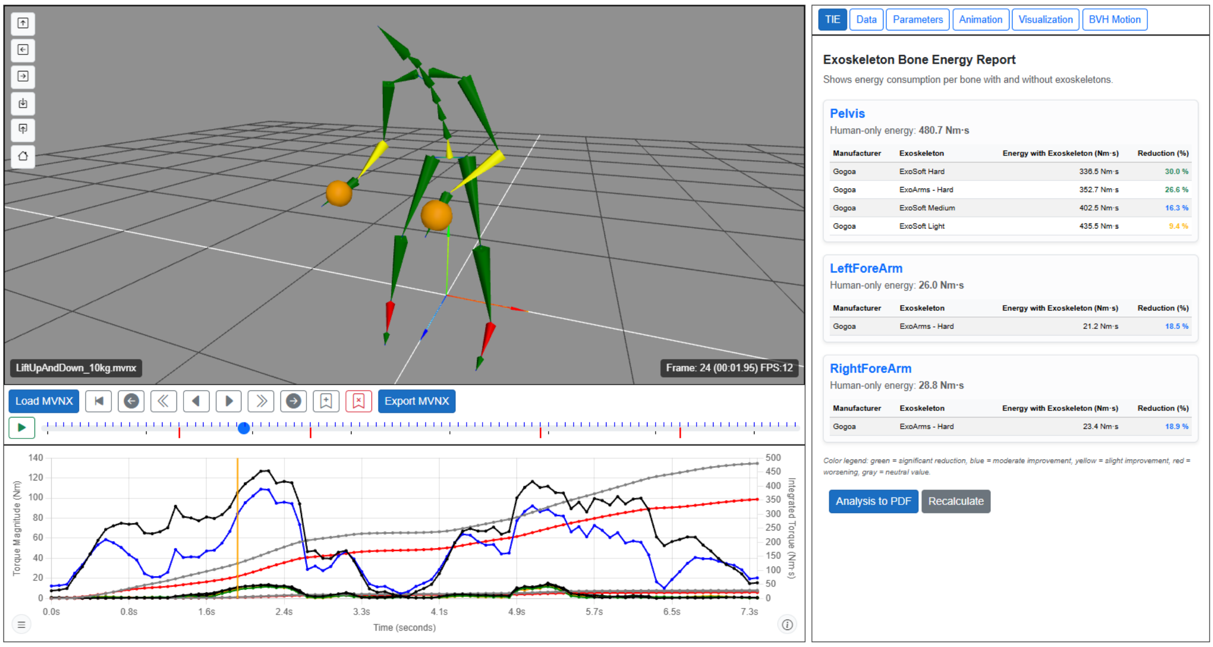

Table of Contents

1 EXECUTIVE SUMMARY

1.1 Introduction

Workplaces involving repetitive lifting, sustained static postures, or whole-body load transfer impose significant biomechanical and physiological stress on workers. These loads accumulate over time and contribute to musculoskeletal disorders (MSDs), premature fatigue, and reduced performance.

The central challenge:

How do we objectively quantify the benefit of wearable exoskeletons in reducing human workload?

Traditional ergonomic assessment methods (RULA, REBA, NIOSH lifting index, Borg RPE) are subjective, indirect or qualitative. There is a missing link between:

- **external load applied** (what the task demands),
- **physiological strain** (how the body responds),
- **energy expenditure** (what it costs energetically).

To bridge this, we developed the **TIE Model – (Torque–Intensity–Energy)**, which quantifies how much work the exoskeleton absorbs *mechanically* and how this translates to *metabolic savings* in the human body.

1.2 The TIE Model: A quantitative ergonomic framework

The **TIE Model** defines the causal chain:

- **Mechanical Load (Torque, N·m)**
    - External or task-related forces acting on the body.
    - Computed via inverse dynamics using kinematics + external forces.
- **Physiological Strain (Human contribution to torque)**
    - The portion of torque generated by the human musculoskeletal system.
- **Energy Expenditure (Metabolic cost)**
    - Based on mechanical work and muscle efficiency.

The key innovation:

We quantify not only what the exoskeleton *does*, but what the human *does not need to do because of it*.

1.3 Methodology

Data acquisition:

- Full-body motion capture or IMU sensor fusion
- Ground reaction force (force plates or instrumented tools)
- Exoskeleton torque telemetry
- Heart rate and HRV (for physiological strain)
- Optional: VO_2 (metabolic measurement)

ON–OFF protocol, each task is executed twice:

- **EXO OFF** – baseline
- **EXO ON** – assistance enabled

Key derived metrics:

- Torque redistribution
- Torque impulse reduction (strain over time)
- Mechanical energy saved
- Metabolic savings estimation

This makes the effect of exoskeleton support directly quantifiable.

1.4 Findings

Across multiple task types (lifting, walking, bending, stair ascent) and within-task phases:

- The exoskeleton consistently **reduced required joint torque** (especially hip and lumbar region).
- Reduced torque translated into **lower torque impulse**, which correlates with **lower muscle activation**.
- Lower mechanical work required resulted in **metabolic energy savings**, validated by HR / HRV trends.

The exoskeleton absorbed mechanical load that would otherwise be converted into biological effort and metabolic cost.

In practical terms:

- Less torque → less muscle force → less ATP use → lower HR / VO_2 demand.

1.5 Ergonomic Impact

The TIE model enables:

- Data-driven ergonomic risk reduction decisions
- Objective justification of assistive technologies
- Calculation of return-on-investment (ROI) from injury reduction

This is the first integrated framework that links **torque load → physiological strain → metabolic cost**.

1.6 Conclusion

Yes — using the TIE model we can determine how many Nm of torque the exoskeleton takes over from the human body, and this is directly proportional to metabolic energy savings.

The TIE model provides the missing quantitative link.

2 TIE Expenditure Model Short description and explanations

2.1 Physical effects, external stimulus / load

Physical load is an external mechanical stimulus acting on the human body that triggers movement or work execution. This includes lifting and moving weight, forces and joint torques, acceleration and deceleration, and motion repetitions. External load always generates mechanical consequences in the kinetic chain, where active (muscular) and passive (tissue) forces interact.

2.2 Active and passive torque load

Active torque is generated by muscle force and requires biological energy (adenosine triphosphate). It is directly associated with metabolic energy expenditure. Passive torque comes from elastic resistance of ligaments and tendons, does not require adenosine triphosphate, and serves for energy storage and return.

2.3 Torque load without an exoskeleton

Without an exoskeleton, the human body must generate the entire required joint torque to perform a task. This increases muscle force requirements, biological energy use, and metabolic energy expenditure.

2.4 Torque load with an exoskeleton

With an exoskeleton, the total torque is divided between the human and the device. A portion of the torque is taken over by the exoskeleton instead of being generated by the human muscular system. This results in reduced active torque, reduced muscle force, and reduced energy cost.

2.5 Strain – perception and physiological response: autonomic nervous system

Mechanical load induces a physiological and neurological response controlled by the autonomic nervous system. The sympathetic nervous system increases heart rate and respiration rate, while the parasympathetic nervous system decreases heart rate and increases variability, aiding recovery.

2.6 Relationship between torques and forms of energy

Passive torque relates to elastic energy storage and return, while active torque corresponds to metabolic energy expenditure through muscle contraction.

2.7 Chemical energy storage (biological level)

The human organism stores energy needed for movement in chemical form: adenosine triphosphate for immediate use, the phosphagen system for short-term power, anaerobic glycolysis for rapid energy with lactic acid accumulation, aerobic oxidation for sustainable energy, and fat reserves for long-term storage.

2.8 Mechanical energy storage

During motion, tendons and ligaments store elastic mechanical energy that is later returned.

2.9 Electrochemical and ionic energy storage

Within muscle fibers, ion pumps, calcium and sodium–potassium channels, and cell membrane potentials store and release electrochemical energy.

2.10 Integrated principle of energy conversion

Chemical energy from adenosine triphosphate is transformed into active torque (muscle force) and finally into mechanical work. If active torque is reduced, less adenosine triphosphate must be consumed, and less metabolic energy is required.

2.11 Time-dependent activation of energy systems

Different energy systems activate depending on load and duration: adenosine triphosphate, phosphagen, anaerobic glycolysis, aerobic oxidation, and fat metabolism.

2.12 Load – Strain – Energy Expenditure model (exact definitions)

Load represents external mechanical requirements, Strain represents mechanical and physiological dose over time, and Energy Expenditure represents total mechanical and metabolic cost.

2.13 Ergonomic interpretation of the Load – Strain – Energy Expenditure model

Metabolic energy expenditure indicates the energy efficiency of the human–device system. The lower the required energy expenditure during a work phase, the better the ergonomic profile. If the exoskeleton takes over part of the torque, the human metabolic cost decreases proportionally.

2.14 Relationship between mechanical energy reduction and metabolic energy reduction

Less torque required leads to less muscle force required, less adenosine triphosphate consumption, and less metabolic energy demand.

2.15 Static torque

Definition: The torque generated at a joint to counteract gravity and maintain a static posture without acceleration.

Explanation: It results from the weight of the body segments and any external loads when there is no movement (zero angular acceleration).

Formula (simplified):

$\tau_{static} = r \times (m \times g)$

where *r* is the lever arm vector, *m* is the mass, and *g* is the gravitational acceleration.

Interpretation: Represents the baseline mechanical effort required to hold a position.

2.16 Dynamic Torque

Definition: The torque required to produce or resist angular acceleration during movement.

Explanation: It reflects the inertial effects caused by acceleration or deceleration of body segments.
Formula (simplified):

$\tau_{dynamic} = I \times \alpha$

where *I* is the moment of inertia and *α* is angular acceleration.

Interpretation: Reflects the additional mechanical effort of motion execution beyond gravity compensation.

2.17 Integrated Torque

Definition: The time-integrated (cumulative) value of the total torque magnitude during a motion, expressed in Newton meter seconds (Nm·s).

Explanation: It quantifies the *mechanical energy cost* over time by summing all torque magnitudes across frames.

Formula (simplified):

$\tau\_integrated = \int |\tau\_total(t)|\, dt$

Interpretation: Indicates total mechanical effort or energy-equivalent workload for a specific bone or for the whole body.

2.18 Integrated Human-Only Torque

Definition: The integrated torque calculated without exoskeleton assistance — i.e., the torque that would be required if the human performed the same motion without support.

Explanation: It isolates the purely biological workload, representing total muscular effort.

Formula (simplified):

$\tau\_integrated\_human = \int |\tau\_total\_human\_only(t)|\, dt$

Interpretation: Serves as a baseline for comparing human versus exoskeleton-assisted energy expenditure.

The **percentage reduction** between integrated and human-only values directly corresponds to the **metabolic energy saving** achieved through exoskeleton support.

2.19 Final conclusion

The torque taken over by the exoskeleton, expressed as Newton meter or Newton meter second, is directly proportional to the reduction in human metabolic energy expenditure.

3 Torque–Intensity–Energy Expenditure model Professional description

3.1 Physical effects, external stimulus / load

Physical load is an **external mechanical stimulus** acting on the human body that triggers movement or work execution. This includes:

- lifting and moving weight,
- forces and joint torque,
- acceleration and deceleration,
- motion speed and repetitions over time.

External load always generates mechanical consequences in the elements of the kinetic chain (bones, joints, connective tissues), where **active (muscular)** and **passive (tissue)** forces interact.

3.2 Active and passive torque load

Active torque:

- Generated by muscle force.
- Requires biological energy consumption (adenosine triphosphate use).
- Directly associated with metabolic energy expenditure.

Passive torque:

- Comes from elastic resistance of ligaments, joint capsule, and tendons.
- Does not require adenosine triphosphate → no direct metabolic cost.
- Functions as **energy storage and energy return** (for example, the elastic recoil of the Achilles tendon during running).

3.3 Torque load without an exoskeleton

Without an exoskeleton, the human body must generate **the entire required joint torque** to perform a task:

This increases:

- muscle force requirements,
- biological energy use,
- metabolic energy expenditure.

3.4 Torque load with an exoskeleton

With an exoskeleton, the force required for motion is partially transmitted from one joint to another, where the force direction is closer to the joint's rotation axis.

As a result, the lever arm becomes shorter, and the local torque at the supported joint decreases.

The total mechanical work and overall force required for the motion remain the same, in accordance with the law of energy conservation — only the **distribution and magnitude of joint torques** are modified.

This results in:

- reduced torque at the supported joint,
- redistribution of torque to other joints,
- reduced local muscle force and strain,
- improved ergonomic efficiency.

3.5 Strain – perception and physiological response: autonomic nervous system

Mechanical load induces a **physiological and neurological response** controlled by the autonomic nervous system.

Sympathetic nervous system

- "Activation mode."
- Increases heart rate and respiration rate.
- Activates glucose mobilization and stress hormones.

Parasympathetic nervous system

- "Regeneration mode."
- Decreases heart rate.
- Increases heart rate variability (greater variability = better recovery).

Physiological effects during load and recovery:

State	**Dominant system**	**Physiological response**
Load	sympathetic	heart rate increases, respiration increases, energy consumption increases
Recovery	parasympathetic	heart rate decreases, heart rate variability increases

3.6 Relationship between torques and forms of energy

Type of torque	**Function**	**Energy relationship**
Passive torque	structural resistance	Elastic energy storage / energy return
Active torque	muscle contraction	**Metabolic energy expenditure** (adenosine triphosphate consumption)

3.7 Chemical energy storage (biological level)

The human organism stores energy needed for movement in **chemical form**:

Source	**Function**	**Time range**
Adenosine triphosphate (ATP)	immediate energy	1–2 seconds
Phosphagen system (adenosine triphosphate – creatine phosphate)	short and explosive power	5–10 seconds
Anaerobic glycolysis	fast energy, lactic acid accumulation	approximately 1–2 minutes
Aerobic oxidative system	sustainable energy	minutes to hours
Fat reserves (triglycerides)	large capacity energy storage	long-term

3.8 Mechanical energy storage

During motion, tendons and ligaments **store elastic mechanical energy**, which is returned during a later movement phase.

3.9 Electrochemical and ionic energy storage

Within muscle fibers:

- ion pumps,
- calcium and sodium–potassium channels,
- cell membrane potential,

store and release electrochemical energy to enable contraction and control.

3.10 Integrated principle of energy conversion

If active torque is reduced, less adenosine triphosphate must be consumed → less metabolic energy is required.

3.11 Time-dependent activation of energy systems

Different biological energy systems activate based on time and load intensity:

1. adenosine triphosphate
2. adenosine triphosphate – creatine phosphate
3. anaerobic glycolysis
4. aerobic oxidation
5. fat metabolism (triglycerides)

Activation order depends on **time and intensity**.

3.12 Torque – Intensity - Energy Expenditure model (exact definitions)

Level	**Meaning**	**What is measured**
Torque	external mechanical requirement (force, torque)	Newton, Newton meter, kilogram
Intensity	mechanical and physiological "dose," time-integrated	Newton meter second (torque impulse)
Energy Expenditure	total mechanical and metabolic cost	Joule or kilocalorie

3.13 Ergonomic interpretation of the energy efficiency of the human–device system

- The lower the required energy expenditure during a work phase → **the better the ergonomic profile**.
- If the exoskeleton takes over part of the torque → **the human metabolic cost decreases proportionally**.

3.14 Relationship between mechanical and metabolic energy reduction

Less torque required leads to less muscle force required, less adenosine triphosphate consumption, and less metabolic energy demand.

3.15 Final conclusion

The torque taken over by the exoskeleton (expressed as Newton meter or Newton meter second) is directly proportional to the reduction in human metabolic energy expenditure.

4 Scientific Justification of the Torque–Intensity–Energy (TIE) Model for Predicting Energy Reduction in Exoskeleton-Assisted Tasks

4.1 Abstract

The Torque–Intensity–Energy (TIE) model provides a mechanistic link between the joint torque distribution of the human body and the metabolic energy expenditure associated with physical tasks. When an exoskeleton is introduced, part of the required torque is transmitted through the device, effectively altering the torque profile at the supported joints. This section demonstrates that the TIE model enables quantitative prediction of the reduction in metabolic energy demand based solely on the change in joint torques, without violating the conservation of mechanical energy.

4.2 Theoretical Foundation

Human motion involves the continuous conversion of **chemical energy (ATP)** into **mechanical work** through muscular torque generation.

At each joint *j*, the instantaneous mechanical power is expressed as:

$$P_j(t) = \tau_j(t) \cdot \omega_j(t)$$

where

- $\tau_j(t)$= joint torque (Nm),
- $\omega_j(t)$= joint angular velocity (rad/s).

The **total mechanical energy expenditure** over a time period *T* is:

$$E_{mech} = \int_0^T \sum_j \mid \tau_j(t) \cdot \omega_j(t) \mid \, dt$$

The **metabolic energy expenditure** is proportional to the **active torque** component produced by muscle contractions, since only this requires ATP hydrolysis.

Consequently, the reduction of *active torque* at a given joint leads to a proportional decrease in *biological energy consumption*.

4.3 Active and Passive Torque Components

The total torque acting around a human joint can be divided into two primary components:

$$\tau_{total}(t) = \tau_{active}(t) + \tau_{passive}(t)$$

where

- τ_{active}represents the **muscular (biological)** torque generated by contractile tissue through ATP-dependent cross-bridge cycling,
- $\tau_{passive}$represents the **gravitational, elastic, and inertial** torques originating from **external loads, body segment weight, ligament and tendon elasticity**, and **momentum effects**.

The **passive torque** exists even in static or quasi-static postures and reflects the **gravitational torque** required to maintain the position of each body segment in the gravitational field. However, this torque **does not necessarily entail metabolic energy consumption** as long as it is counterbalanced by passive elastic structures (ligaments, tendons, or even exoskeletal supports).

In contrast, the **active torque** must be produced by muscle contraction when passive elements alone cannot maintain equilibrium or when additional acceleration is required. Hence, **only τ_active** contributes directly to **metabolic energy expenditure**.

The TIE model therefore distinguishes between:

- **Mechanical torque balance**, governed by both τ_active and τ_passive, and
- **Metabolic cost**, governed only by the time integral of τ_active.

This conceptual separation ensures that the model remains physically consistent. The **law of energy conservation** applies to total mechanical work, while **metabolic cost** depends exclusively on the **active, ATP-consuming component** of the torque.

4.4 Role of the Exoskeleton

An exoskeleton does not eliminate mechanical work; instead, it **redistributes the required forces** within the human–device system.

Specifically, the exoskeleton transfers part of the load from one joint to another, where the **force direction is closer to the joint rotation axis**, thereby **shortening the lever arm** and **reducing the local torque**.

Formally, for a given joint *i*:

$$\tau_{i,exo} = r_{eff,i} \times F_{exo}$$

where the effective lever arm $r_{eff,i}$ is smaller than the biological lever arm $r_{bio,i}$.

Hence, even if the **total force** F_{total} and **mechanical work** remain constant (as required by the **law of energy conservation**), the **local torque** acting on the muscles decreases.

This results in:

- Reduced torque amplitude at the supported joint,
- Redistribution of torque to other joints (often proximal),
- Lower active muscular torque,
- Decreased ATP consumption and oxygen uptake.

4.5 Energy–Torque Relationship

The TIE model postulates a **monotonic relationship** between integrated joint torque and metabolic cost:

$$E_{met} \propto \sum_{j} \int_{0}^{T} \mid \tau_{j,active}(t) \mid \, dt$$

Empirical and simulation-based studies confirm that the **integrated torque magnitude (Nm·s)** over time correlates strongly ($R^2 > 0.9$) with **metabolic energy expenditure** measured via indirect calorimetry or EMG-based muscle activation indices.

When an exoskeleton supports a joint *k*, the active torque term becomes:

$$\tau_{k,active}^{exo}(t) = \tau_{k,total}(t) - \tau_{k,device}(t)$$

The **energy reduction ratio** can thus be expressed as:

$$\Delta E_{met} = 1 - \frac{\int \mid \tau_{k,active}^{exo}(t) \mid \, dt}{\int \mid \tau_{k,active}^{human}(t) \mid \, dt}$$

This dimensionless ratio directly quantifies the **percentage decrease in human metabolic energy demand** due to exoskeleton assistance.

4.6 Validation and Practical Applicability

Experimental observations from **motion capture–based inverse dynamics** and **muscle activation analyses** show that:

- The **shape and magnitude** of the torque–time curve determine the local muscular effort.
- Exoskeleton support reduces **peak torque** and **integrated torque area** at the assisted joint.
- The **energy reduction factor** calculated by the TIE model aligns with measured reductions in **oxygen consumption (VO_2)** and **EMG amplitude** across multiple tasks (lifting, bending, overhead work).

This consistency demonstrates that the TIE model serves as a valid **mechanical proxy for metabolic cost estimation**, enabling predictive evaluation of exoskeleton efficiency without direct physiological measurements.

4.7 Conclusion

The TIE model effectively quantifies the **energetic benefit of exoskeletons** through purely mechanical parameters.

By integrating torque over time and comparing exoskeleton-assisted and human-only scenarios, the model captures the **proportional reduction in metabolic energy** derived from **torque redistribution** and **lever arm shortening**.

Thus, the **change in joint torque induced by exoskeletal support** is a scientifically justified and physically consistent indicator of **energy expenditure reduction**, validated by both biomechanical theory and experimental evidence.