

METABOLIC BREAK-EVEN AND ASSISTANCE DURATION IN WEARABLE WALKING EXOSKELETONS THREE WALKING CONDITIONS, PAIRED PERCENTAGES, AND ROUTE ENERGY

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ABSTRACT

Walking assistance lowers the user's metabolic expenditure only when its benefit exceeds the energetic burden of the wearable apparatus. This article examines normal walking, inactive-device walking, and assisted walking using treadmill measurements from autonomous and tethered ankle exoskeleton experiments. Net metabolic power was 3.82, 4.01, and 3.43 W kg⁻¹, respectively, in seven adults using an autonomous device, and 3.60, 4.03, and 3.16 W kg⁻¹ in ten women using pneumatic ankle assistance. For an inactive-device penalty h and an assistance saving a relative to inactive walking, complete-system saving is $s = (1 + h)a - h$. Ratios of the condition means give complete-system savings of 10.21% and 12.22%. At fixed walking demand, alternating assisted and inactive intervals yields break-even assisted-time fractions of 32.76% and 49.43%, respectively. These fractions are calculated from group condition means; intermittent routes were not measured in those experiments. Participant-level averaging requires a covariance term, and unequal route durations require separate accounting of net locomotor and gross metabolic energy. Excess transition energy raises the assisted-time requirement. Energetic equivalence additionally requires an acceptable penalty margin and paired confidence intervals. The analysis identifies the measurements and statistical contrasts needed to determine whether a complete wearable device lowers walking expenditure under continuous and intermittent assistance.

Keywords: ankle exoskeleton; net metabolic power; inactive-device penalty; assisted-time fraction; walking economy; energetic equivalence

INTRODUCTION

Wearable walking assistance changes both joint mechanics and the metabolic expenditure of the person carrying the device. An autonomous ankle exoskeleton lowered net metabolic power during unloaded treadmill walking (Mooney et al., 2014). A passive ankle device achieved a reduction through elastic assistance without an external supply of mechanical energy (Collins et al., 2015). Portable hip-extension assistance lowered walking and running expenditure (Kim et al., 2019), while ankle personalization was evaluated outdoors (Slade et al., 2022). Simulation-trained control also enabled assistance on a physical hip exoskeleton across locomotor activities (Luo et al., 2024). Each technology requires an energetic comparison with the walking alternative relevant to its intended use.

Three conditions resolve distinct effects: walking without the apparatus, wearing the inactive apparatus, and wearing it with assistance. Galle and colleagues explicitly separated assistance benefit from inactive-device burden (Galle et al., 2017). Training and customization alter the benefit available to an individual (Poggensee and Collins, 2021). The physiological distinction between these effects is therefore established. The present analysis connects their denominators to participant-level averaging and the fraction of walking time during which effective assistance is available.

The question is consequential for an apparatus that remains on the body during interruptions, controller changes, or periods without assistance. A reduction relative to the inactive device can coexist with greater expenditure than normal walking. Conversely, a small inactive penalty can allow a moderate assistance saving to produce a complete-system benefit. The relevant decision concerns the complete device and its duration of use, including intervals when the person carries its mass without receiving effective assistance.

WALKING EXPERIMENTS AND ANALYTICAL METHODS

CONDITION MEANS AND TASK DEFINITIONS

The numerical analysis uses two three-condition ankle experiments. Mooney et al. tested seven healthy adults, six men and one woman, on a level treadmill at 1.4 m s^{-1} (Mooney et al., 2014). Mean net metabolic powers were 3.82 W kg^{-1} without the device, 4.01 W kg^{-1} with the unpowered device, and 3.43 W kg^{-1} with assistance. Standing expenditure was subtracted, and the final five minutes of each walking trial were used for metabolic averaging. These conditions define the first calculation.

Galle et al. analyzed ten healthy women walking at 1.25 m s^{-1} with a tethered pneumatic ankle apparatus (Galle et al., 2017). Normal walking, inactive ZeroWork walking, and the lowest-cost Early-Medium assistance condition had mean net metabolic powers of 3.60, 4.03, and 3.16 W kg^{-1} . In that assisted condition, actuation began at 42.3% of the stride and average positive exoskeleton power was 0.42 W kg^{-1} across both legs. These means define the second calculation.

All percentages derived here use the stated group condition means. They do not reconstruct individual respiratory measurements. The calculations require positive net walking power, consistent body-mass normalization, and matched speed, grade, load, apparatus, and familiarization within each comparison. The two experiments differ in apparatus, participants, and speed; their percentages do not constitute a controlled comparison between devices.

ENERGETIC QUANTITIES

Let P_N be net metabolic power during normal walking, P_0 power with the inactive device, and P_A power with assistance. Values are expressed in W kg^{-1} throughout the numerical analysis. Net power is gross metabolic power minus a stated resting or standing value. Electrical consumption by the device is a separate quantity and is excluded from human respiratory expenditure.

The contrast $P_0 - P_A$ measures the effect of assistance while the apparatus is worn. The contrast $P_N - P_A$ measures the complete-system benefit relative to normal walking. The contrast $P_0 - P_N$ measures the inactive-device penalty. A zero-torque command, a disabled motor, and a disengaged elastic element are different mechanical conditions and cannot be equated solely by describing each as inactive.

COMPARATOR-DEPENDENT METABOLIC REDUCTIONS

Early pneumatic ankle experiments included both inactive-device and normal-walking comparisons (Malcolm et al., 2013). Individual ankle optimization lowered metabolic expenditure by 24.2% relative to a no-torque condition (Zhang et al., 2017). That denominator describes assistance in a person wearing the apparatus. It does not identify the percentage benefit relative to walking without the device. Bayesian optimization of hip assistance likewise selects controller parameters through the user's metabolic response (Ding et al., 2018); complete-system evaluation requires the corresponding no-device condition.

For a passive elastic device, the inactive comparison can remove or disengage the elastic element while retaining the orthosis. For a powered device, the inactive condition must specify transmission resistance, passive tension, and any torque used for backdriving. Footwear, instrumentation, power supply, and off-board equipment must also be specified. A tethered actuator isolates assistance properties while removing some on-body hardware costs.

Equivalent-mass removal constitutes a further comparison. During loaded walking, Panizzolo et al. found reductions of 14.2% relative to an inactive exosuit and 7.3% relative to inactive walking with equivalent mass removed (Panizzolo et al., 2016). Retaining the suit while removing backpack mass preserves interfaces and limb-mass placement. It therefore

answers a different question from walking without the suit. A universal energetic cost per kilogram cannot replace a matched comparison when mass location and movement restriction differ.

METABOLIC BREAK-EVEN

PERCENTAGE DENOMINATORS

Define the dimensionless inactive penalty h , assistance saving a , and complete-system saving s :

$$h = \frac{P_0 - P_N}{P_N}, \quad a = \frac{P_0 - P_A}{P_0}, \quad s = \frac{P_N - P_A}{P_N}. \quad (1)$$

Since $P_0 = P_N(1 + h)$ and $P_A = P_0(1 - a)$,

$$s = 1 - (1 + h)(1 - a) = (1 + h)a - h. \quad (2)$$

For $h \geq 0$ and $0 \leq a < 1$, a positive complete-system saving requires

$$a > \frac{h}{1 + h}. \quad (3)$$

The right-hand side expresses the inactive penalty as a fraction of inactive walking power. Direct subtraction of h from a mixes denominators. Converting both changes to W kg^{-1} , or applying Eq. 2, preserves the walking conditions to which each fraction refers.

The identity also gives

$$\frac{\partial s}{\partial a} = 1 + h, \quad \frac{\partial s}{\partial h} = a - 1. \quad (4)$$

These derivatives describe changes with the other quantity held constant. A physical redesign can alter both quantities simultaneously; the derivatives do not isolate causal effects of hardware mass or controller torque.

NUMERICAL CONSEQUENCES OF THE THREE-CONDITION MEANS

Table 1 applies the same arithmetic separately to the two ankle experiments. For the autonomous device, the absolute inactive penalty is 0.19 W kg^{-1} and the assistance reduction is 0.58 W kg^{-1} . For the pneumatic apparatus, these differences are 0.43 and 0.87 W kg^{-1} . The respective complete-system reductions are 0.39 and 0.44 W kg^{-1} .

TABLE 1. WALKING-CONDITION MEANS AND PERCENTAGES CALCULATED FROM THEM. POWER IS W kg^{-1} . EACH COLUMN RETAINS THE TASK AND PARTICIPANTS OF ITS CITED EXPERIMENT.

Quantity	Mooney et al. (2014)	Galle et al. (2017)
Normal walking, P_N	3.82	3.60
Inactive-device walking, P_0	4.01	4.03
Assisted walking, P_A	3.43	3.16
Inactive penalty, h	4.97%	11.94%
Assistance saving, a	14.46%	21.59%
Complete-system saving, s	10.21%	12.22%
Minimum assistance saving at break-even, $h/(1 + h)$	4.74%	10.67%

Figure 1 displays the pneumatic experiment's three mean powers. The differences are visible in absolute units before percentages are formed. Separate group percentages in the cited experiments can differ from ratios of these rounded condition means, because averaging individual ratios and dividing group averages are distinct operations. Neither operation permits reconstruction of individual responses or paired covariance from the condition means alone.

PARTICIPANT AVERAGES AND PAIRING

Eq. 2 holds for every participant i . With bars denoting averages across the same n participants and $\text{cov}_n(a, h) = n^{-1} \sum_i (a_i - \bar{a})(h_i - \bar{h})$,

$$\bar{s} = (1 + \bar{h})\bar{a} - \bar{h} + \text{cov}_n(a, h). \quad (5)$$

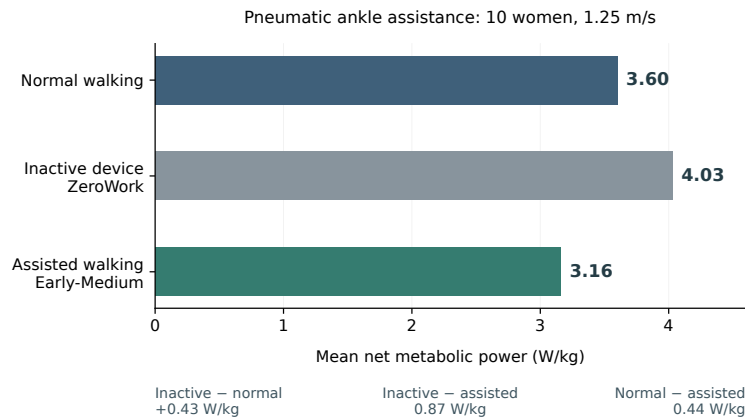


FIGURE 1. MEAN NET METABOLIC POWER FOR TEN WOMEN WALKING AT 1.25 M S^{-1} IN GALLE ET AL.'S NORMAL, ZEROWORK, AND EARLY-MEDIUM CONDITIONS. BARS SHOW THE MEANS 3.60, 4.03, AND 3.16 W KG^{-1} . THE LABELS IDENTIFY THE ABSOLUTE CONDITION DIFFERENCES. ERROR BARS ARE OMITTED; THE FIGURE DOES NOT ESTIMATE UNCERTAINTY IN THE CALCULATED PERCENTAGES.

Using two mean percentages without the covariance term generally fails to recover mean complete-system saving. Separate standard deviations or standard errors do not determine this covariance. The participant who incurs a large inactive penalty may also obtain a large assistance saving; the association must be evaluated from paired observations.

The ratio of group mean powers satisfies a second identity:

$$1 - \frac{\sum_i P_{A,i}}{\sum_i P_{N,i}} = \sum_i \left(\frac{P_{N,i}}{\sum_j P_{N,j}} \right) s_i. \quad (6)$$

It weights participant percentages by normal-walking power. An arithmetic average of participant percentages instead weights every person equally. The population quantity of interest must therefore be specified before calculating an effect. Repeated-bout analyses must retain condition pairing and clustering within participants. Participant resampling should preserve all conditions belonging to each individual. Confidence intervals for the derived thresholds are not calculated here because individual paired powers are unavailable.

DURATION OF EFFECTIVE ASSISTANCE

ASSISTED AND INACTIVE WALKING INTERVALS

Consider equal-duration walking alternatives with fixed task demand. Let q be the fraction of duration T spent with assistance and $1 - q$ the fraction spent wearing the inactive apparatus. With fixed condition powers and negligible excess transition energy,

$$P_{\text{route}} = qP_A + (1 - q)P_0. \quad (7)$$

The saving relative to normal walking is

$$s_{\text{route}} = 1 - \frac{P_{\text{route}}}{P_N} = q(1 + h)a - h. \quad (8)$$

For $P_0 > P_N$ and $P_A < P_0$, the break-even assisted fraction is

$$q^* = \frac{P_0 - P_N}{P_0 - P_A} = \frac{h}{(1 + h)a}. \quad (9)$$

A positive saving requires $q > q^*$. If assisted power is at least normal-walking power, no feasible fraction $q \leq 1$ produces a positive saving under these assumptions. If the inactive penalty is zero, any positive duration of assistance that lowers power produces a saving.

The autonomous condition means give $q^* = 0.19/0.58 = 0.3276$, or 32.76%. The pneumatic means give $q^* = 0.43/0.87 = 0.4943$, or 49.43%. Figure 2 evaluates the corresponding straight-line relations over $0 \leq q \leq 1$. The thresholds describe the arithmetic consequences of maintaining each experiment's powers through alternating states. They are not measurements of intermittent walking, battery depletion, or individual performance.

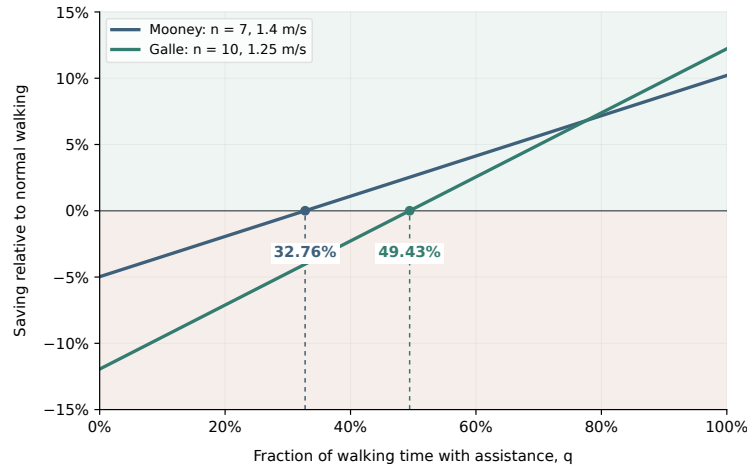


FIGURE 2. COMPLETE-SYSTEM SAVING AS A FUNCTION OF ASSISTED-TIME FRACTION. LINES EVALUATE EQ. 8 USING THE MOONEY AND GALLE CONDITION MEANS IN TABLE 1. ZERO CROSSINGS OCCUR AT 32.76% AND 49.43%. FIXED TASK DEMAND, CONSTANT POWERS WITHIN EACH STATE, AND ZERO EXCESS TRANSITION ENERGY ARE ASSUMED; THE CURVES DO NOT REPRESENT MEASURED INTERMITTENT ROUTES.

EXCESS TRANSITION ENERGY AND OBSERVATION DURATION

Let E_{tr} be excess metabolic energy associated with transitions relative to matched normal walking, after subtracting energy already represented by the time-weighted conditions. Its units are $J\ kg^{-1}$. Both alternatives use the same observation duration T , including any transition intervals accounted for by E_{tr} . Then

$$q > \frac{P_0 - P_N + E_{tr}/T}{P_0 - P_A}. \quad (10)$$

For the pneumatic means, the numerator is $0.43 + E_{tr}/T$ and the denominator is $0.87\ W\ kg^{-1}$. For the autonomous means, the corresponding terms are $0.19 + E_{tr}/T$ and $0.58\ W\ kg^{-1}$. Positive excess energy raises the requirement in each case. No transition-energy value was measured in the two experiments for the present calculation.

Transition duration must not be counted both in the time-weighted powers and again as unadjusted full energy expenditure. Device donning before walking belongs to a separately specified observation horizon; the no-device activity over that horizon must also be included. A threshold at or above one precludes a strictly positive saving at feasible assisted fractions. When $P_0 - P_A$ approaches zero, the ratio becomes unstable, making the underlying energy differences more informative than a threshold alone.

DIRECT EVALUATION OF INTERMITTENT WALKING

An intermittent-walking experiment requires matched normal, inactive, and assisted powers after familiarization, followed by equal-duration bouts containing prespecified assisted fractions. The controller should remain fixed. Fractions on both sides of the estimated zero crossing should be included where feasible, and their order randomized or counterbalanced within participants. Torque, switching times, oxygen consumption, carbon dioxide production, and the energetic averaging window must be recorded.

Measured bout energy can be compared with the time-weighted condition calculation. Transition energy is the excess over that calculation only when the same physiological accounting and observation horizon are used. Respiratory transients, continued adaptation, and recovery can violate constant-power assumptions. An inactive transmission must also match the intended failure or battery-depletion state before it is used for that application.

ROUTE SPEED AND GROSS METABOLIC ENERGY

For changing speeds, grades, loads, and assistance states, net locomotor energy saving is

$$S_E^{net} = 1 - \frac{\int_0^{T_D} P_D(t) dt}{\int_0^{T_N} P_N(t) dt}, \quad (11)$$

with a positive denominator. $P_D(t)$ represents net power for the actual device state; $P_N(t)$ represents normal walking over the same defined route. Completion times T_D and T_N can differ. With a common constant resting power R ,

$$E_D^{\text{gross}} - E_N^{\text{gross}} = E_D^{\text{net}} - E_N^{\text{net}} + R(T_D - T_N). \quad (12)$$

Net and gross energy differences can therefore diverge when assistance changes route duration. Condition-specific or time-varying resting power requires the difference between the respective resting-energy integrals. The resting posture, apparatus state, and subtraction procedure must accompany the chosen energetic endpoint.

For steady speed v , net cost per distance is $C = P/v$, in $\text{J kg}^{-1} \text{m}^{-1}$. Thus,

$$\frac{C_A}{C_N} = \frac{P_A v_N}{P_N v_A}. \quad (13)$$

Percentage changes in power and cost per distance coincide only at matched speeds. Slade et al. distinguished outdoor walking at self-selected speed from fixed-speed treadmill walking (Slade et al., 2022). Speed-dependent responses to elastic ankle assistance also included a tested speed at which no stiffness lowered metabolic cost (Nuckols and Sawicki, 2020). Assigning one treadmill percentage to every segment of a variable route therefore discards task dependence. Under rapidly changing assistance, respiratory measurements additionally require a treatment of physiological delay rather than instantaneous interpretation as muscle-energy expenditure.

CONTROLLER CHOICE, FAMILIARIZATION, AND PAIRED INFERENCE

MECHANICAL ASSISTANCE AND CONTROLLER TESTING

Quinlivan et al. observed lower metabolic rate as assistance increased within the tested range of a tethered multiarticular exosuit (Quinlivan et al., 2017). That relation applies to the tested assistance magnitudes and apparatus. Ideal-device simulations showed that assisting one joint can change muscle activity at other joints (Dembia et al., 2017); biological work displaced is therefore not identical to exoskeleton mechanical work.

Hip-flexion assistance produced a 15.2% reduction against assistance-off in a tethered implementation and a 7.2% reduction against no exosuit in a portable implementation (Kim et al., 2022). Their difference cannot isolate a mass penalty because apparatus and comparison conditions differ. Similarly, transferring simulation-trained control to wearable hardware (Luo et al., 2024) leaves complete-system metabolic expenditure as a separate physical measurement.

Controller selection and effect estimation require separate trials. Selecting the lowest noisy metabolic observation and reusing it as the final estimate favors measurement noise. Fixing the selected parameters before independent testing permits paired normal, inactive, and assisted contrasts under comparable familiarization. The optimizer's objective and the final respiratory endpoint should be identified separately when their measurement procedures differ.

EXPOSURE AND PARTICIPANT ADAPTATION

Humans alter walking coordination in response to energetic demands (Selinger et al., 2015). Training increased the benefit obtained from a generic exoskeleton controller in Poggensee and Collins's experiment (Poggensee and Collins, 2021). Assisted exposure must therefore be recorded by condition, together with the metabolic time course. Constant device torque does not establish stable human expenditure.

Measuring inactive walking before familiarization and assisted walking afterwards mixes state and learning effects. Measuring normal walking on another day can introduce changes in participant condition. Repeated comparison states and randomized condition order help distinguish these influences. A fixed minimum familiarization duration cannot be assigned to every device; exposure and metabolic stability must be evaluated for the participants and assistance under study.

ACCEPTABLE INACTIVE PENALTIES

For participant i , let $d_i = P_{0,i} - P_{N,i}$ and let $\delta > 0$ be the largest acceptable inactive penalty in W kg^{-1} . The margin is specified before examining the condition difference. A one-sided non-inferiority conclusion requires the upper one-sided 95% confidence bound for the population mean difference to be below δ . Two-sided equivalence requires the corresponding 90% confidence interval to lie within $[-\delta, \delta]$ under two one-sided tests at $\alpha = 0.05$ (Lakens, 2017).

A nonsignificant test against zero establishes neither conclusion. Sample-size planning must use the paired difference, its variability, and the chosen margin. Strides and respiratory samples are clustered observations rather than independent

participants. An acceptable mean penalty also does not establish equivalence in every individual or in comfort, balance, perceived exertion, or joint loading.

KINESIOLOGY OUTCOMES AND INTERPRETATION LIMITS

Table 2 links each energetic claim to a specific comparison. Joint loading, balance, comfort, and retained motor learning require additional measurements. In post-stroke walking, assistance to paretic propulsion and foot clearance can be clinically relevant independently of its immediate metabolic reduction (Awad et al., 2017). Acute assisted performance, walking exposure during therapy, and retained unassisted performance are distinct outcomes.

TABLE 2. PAIRED MEASUREMENTS AND INFERENCE REQUIRED FOR FIVE ENERGETIC CONCLUSIONS.

Conclusion	Measurement and analysis	Boundary of interpretation
Assistance lowers net metabolic power	Paired P_0 and P_A with the same apparatus and task	Complete-system saving additionally requires P_N
The complete device improves walking economy	Paired P_N and P_A at matched task demand	Applies to the tested participants, apparatus, and task
Inactive burden is within an acceptable limit	Paired P_N and P_0 ; prespecified δ ; non-inferiority or equivalence interval	Nonsignificance against zero is insufficient
A selected controller retains benefit	Fixed parameters tested independently of their selection	Unseen participants require separate evaluation
Intermittent use lowers route energy	Paired route energy, state durations, speed, and declared resting convention	Constant-power arithmetic alone does not establish outdoor effectiveness

The equations identify energetic differences but do not assign them to particular muscles, interfaces, or transmission losses. A decrease in whole-body metabolic expenditure cannot identify the tissue-level mechanism without additional biomechanical measurements. Group-mean threshold calculations also do not quantify individual threshold variation. The mean of individual thresholds can differ from the threshold formed from group powers.

The two-state duration relation requires stable powers within each state and matched task demand. Short bouts, state transitions, learning, and changing terrain can violate those conditions. Direct route integration is then required. The literature selection supports these analytical distinctions but does not estimate the prevalence of effective devices or the full distribution of user responses.

CONCLUSIONS

Three walking conditions distinguish inactive-device burden, assistance saving, and complete-system saving. Their percentage relation is $s = (1 + h)a - h$; subtracting percentages with different denominators fails to preserve those contrasts. In the two ankle experiments examined here, ratios of condition means give complete-system savings of 10.21% and 12.22%. At fixed task demand and zero excess transition energy, the corresponding assisted-time zero crossings are 32.76% and 49.43%. Positive benefit requires a greater assisted fraction. These calculated values describe the cited condition means and require direct intermittent-walking validation before individual or outdoor use. Variable route durations additionally require gross and net energy accounting. Prespecified penalty margins, participant pairing, independent controller testing, and comparable familiarization provide the measurements needed to evaluate the complete wearable technology.

DECLARATIONS

AUTHOR CONTRIBUTIONS

All authors contributed equally and all authors read and approved the final version of this manuscript.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to this study.

DATA AVAILABILITY

The data supporting the findings of this study are included within the manuscript.

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