

Interaction-based rapid heuristic optimization of exoskeleton assistance during walking

Corresponding Author: Dr Juanjuan Zhang

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This manuscript introduces a new method for human-in-the-loop exoskeleton assistance optimization using gradient descent based on real-time human joint moment estimates. This approach converges within a few minutes, which is much faster than previous methods, and the controller does not require spline parameters. While the authors' approach did significantly reduce user energy expenditure, the impact of this work is unclear unless the authors further clarify their results compared to prior work.

Impact/Claims: The author's make several claims about the optimization method presented in this work. I agree that their approach converges much faster than previous methods and shows promise for generalizing beyond level-ground, normal-speed walking; however, without adding more discussion, it's unclear how this work compares to state-of-the-art methods for metabolic cost optimization and multi-task exoskeleton control.

- The work of Slade et al (Nature 2022) also introduced a method for rapidly optimizing user energy expenditure without the need for metabolic measurements. The authors correctly note that their work converges much faster than that of Slade et al, but it is potentially less effective. If so, please add discussion further detailing the trade-offs between these two methods.
- The authors state that their approach is non-parametric but should make it clear that this method is still dependent on a gait phase estimate and on known ambulation conditions (e.g., walking vs running, ground slope, walking speed).
- The work of Gasparri et al (TNSRE 2019) and follow-up work by Dr. Lerner's group has shown similar metabolic benefits by imitating the biological ankle moment. Their approach may also generalize better since it is not dependent on gait phase or other ambulation information. The authors should make it clear why the added complexity of their controller is advantageous.
- Nit. The authors should clarify that the results presented in the Abstract are using an exoskeleton emulator (i.e., offboard actuation and power).

Methods: The methods presented in this manuscript are clear and rigorous. I have a few small comments for additional clarification.

- Please clarify why the majority of the study was conducted using only unilateral assistance? This makes it very hard to compare to the more recent and very relevant work of Slade et al. (Nature 2022). I would highly recommend additional metabolic testing using the bilateral ankle exoskeleton to improve the comparison to state-of-the-art methods.
- Please justify why the order of assistance conditions was fixed across participants during the double reversal experiments.

Statistics: The authors use paired t-tests for evaluating user outcomes across multiple pairwise comparisons. These tests should be updated with a method that corrects for the family-wise error rate (e.g., by applying a Bonferroni correction).

Reviewer #3

(Remarks to the Author)

This study proposes a rapid heuristic optimization algorithm for exoskeleton-assisted walking, which uses joint torque as a feedback signal to optimize assistance by minimizing the combination of human efforts, exoskeleton inputs, and assistance-incurred biomechanical changes. This study achieves real-time biomechanics evaluation under different gaits, devices/joints, and outdoor environments while improving user comfort and reducing deployment costs. The manuscript is clear, organized, and rich in experiments, and the language is standardized.

Here, the reviewer lists some advice and comments to help improve the manuscript:

The manuscript claims realized a gradient descent optimization that minimized the combination of human efforts. It is a little bit misleading reader since human efforts are strongly relevant to muscle activity. It is highly recommended to clarify the key hypothesis of the work, and what the objective function and constraints of the proposed optimization method. In addition, maybe clarify the below sentence in the abstract "by minimizing human efforts while constraining exoskeleton assistance and joint mechanics"

2. The setting of the parameter p lacks an experimental basis. The paper assumes $p=0.05$, but the actual human adaptability may be more complicated. It is recommended to analyze the p value through experiments.

3. In the outdoor exoskeleton assistance optimization experiment, the feedback signal was changed from τ_{joint} to τ_{human} , but the impact of this replacement on the optimization was not verified. It is recommended that the effects of outdoor torque estimation error on exoskeleton assistance optimization be analyzed.

4. Modification of format:

1) Variables should be uniformly italicized, and different variables should be represented by different symbols. For example, participant number n should be uniformly italicized. The symbols for the participant number and current stride number are both n , and the symbols for the joint maker and pressure reading are both P . It is recommended to distinguish them.

2) Many formulas in the paper are not numbered. It is recommended to number all formulas.

3) The reference format is unified. For example, the format of the first letter of the journal name should be uniformly represented.

Reviewer #4

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Communications Engineering program to promote peer review training and provide appropriate recognition to early career researchers who co-review manuscripts.

Reviewer #5

(Remarks to the Author)

This work presents an exoskeleton assistance strategy to reduce human muscular effort and metabolic cost. The controller torque dynamically converge to 30-50% of the net joint torque measured by force pleated or pressure insole. Using a portion of biological joint torque as the exoskeleton assistance torque is not novel. However, the dynamic convergence to the continuously measured net joint torque is interesting and considerable. Given that human tries to keep the net torque optimized and with very gradual changes in exoskeleton torque, we can assume the net torque is still optimized and therefore net torque is a good candidate for assistance. This is a novel perspective which is worthy of consideration. Moreover, the relation between this very simple approach and the way it could be considered as a gradient descend-based minimization of a cost function based on human and exoskeleton effort as well as deviation from the human un-assisted torque is interesting, which however needs to be explained better. My main concern about the paper is, however, lacks clarity and complex and sometimes vague language. I found it hard to understand the terminologies in the first encounter and I'll suggest some points to help. In general, I find this work valuable for the field.

1- The way I understand this method is that the exoskeleton controller exponentially smoothens toward a weighted average of zero assistance torque (initial torque recorded from the user) and the net torque recorder from the previous stride. This is very simple, and I think there is nothing wrong with a method being simple. If the exo intervention is slightly changing in each stride, then human will optimally adapt to the intervention and then using the net recording torque as the exo torque (average of course) will make sense. I think this is a strong point about the paper but is not transferred efficiently due to lack of clarity.

2- Given that K_{nom} and K_{dev} are equal and between 0.3 and 0.5 according to extended data table 2, then the averaging process is supposed to track 30-5-% of the average torques of the last stride and no-assisted walking. Extended data Fig.8 supports this. I think such design (that the exo will converge to a certain amount of torque) should be clarified not mistaken with something that is the output of optimization.

3- The gradient descend optimization equivalency of the simple averaging method is interesting, I encourage authors to clarify few points: 1) given that $p(k)$ is variable and k_{nom} and k_{dev} are fixed, it means that $\lambda_{1,2,3}$ are variable with respect to k which is not considered in Eq.2.

4- One may ask what happens if you just apply 30-50 percent of zero-torque walking to the user (feedforward assistance) without exponential smoothing? Such comparison would be interesting and shows which of the human biological torques or the gradual update of the controller are more important.

5- Introduction of the paper does not set the stage well for the controller. After line 68, the introduction becomes technical (more like methods) and uses terms that are not familiar and confusing when the reader sees them the first time. For example:

5-1- Line 69-70, "replacing human effort with exoskeleton assistance is" I could not understand this sentence before reading the whole paper.

5-2- Lines 70-73. The same issue. English needs improvement.

5-3- Line 75: it mentions that the assisted joint torque was made dominant in the learning process while in all the case k_{nom} and k_{dev} are equal. So the exo torque will converge to the weighted average of the unassisted and assisted torques.

6- Your work is somehow related to feedforward control where desired net torque is estimated and applied by the exoskeleton. However, instead of estimating that, you measure it using force plate and converge to it by an exponential averaging. I see the contribution, but this is not fundamentally different than those works. Discussing this connection would help setting the stage for your contribution in the introduction.

7- Terminologies such as normal-shoes walking (-> no exo walking), premature torque (passive exo torque) are confusing. I could understand line 84-85 only when I read the whole paper. I suggest authors to move this sentence to the method part and try to explain their actual contribution (measuring the net torque and applying a portion of that gradually converged using an exponential averaging method) in a more clear and straight forward way.

8- There are some works which is worthy of discussion in the intro:

[1] Durandau, Guillaume, et al. "Neuromechanical model-based adaptive control of bilateral ankle exoskeletons: biological joint torque and electromyogram reduction across walking conditions." *IEEE Transactions on Robotics* 38.3 (2022): 1380-1394.

[2] Shushtari, M., Foellmer, J. & Arami, A. Human-exoskeleton interaction portrait. *J NeuroEngineering Rehabil* 21, 152 (2024). <https://doi.org/10.1186/s12984-024-01447-1>

10- About the sentence is line 502-504, why increase in net joint torque as a result of increase in exoskeleton joint torque means assistance? what if the user is resisting? A simple example,

11- Line 506: what does efficiently mean here?

12- Line 540: "The value of $K_{dev} = K_{nom}$ for the optimization was set based on the amount of assistance the participant was willing to tolerate ([0.175, 0.25])." K_{dev} and k_{nom} is more than 0.3 according to extended data table 2. The range seems to be wrong. Please clarify.

13- Line 551: referring "NW-ZT-Gen-Opt-Opt-Gen-ZT-NW", these are not defined previously as I can see.

14- How k (time index) is estimated? Is it based on time? If so, how sensitive this approach is to variations (transitions) in gait timing? Did you use a gait phase estimator?

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Thank for you thoroughly addressing each of my comments. The corresponding updates to the manuscript, especially the additional experiments, help clarify how the proposed approach compares to prior literature; however, I have a few remaining comments.

1. When mentioning that the metabolic cost reductions in this study were similar to those of Slade et al., please make it clear that Slade's metabolic reductions were about twice as large but used bilateral assistance compared to the unilateral assistance in this study.

2. I greatly appreciate the addition of the proportional joint torque experiments, which greatly help compare this approach to prior work; however, I have a few concerns about the methods and interpretation of these results.

a. In "Comparison to assistance proportional to unassisted joint torque," I would have expected the authors' approach be compared to the method that applies a portion of the real-time torque (more representative of the state-of-the-art in proportional joint torque control) opposed to a portion of the open-loop baseline from zero-torque. Please justify why this was used instead.

b. "However, their open-loop nature places the burden of achieving this synergy entirely on the user's neuromuscular system. A user failure at reacting cooperatively and instantaneously may incur system instability and human danger." I would not consider the referenced controllers that actively estimate real-time joint torque "open loop" since they immediately react to changes in the user's motion. Please clarify that the more recent approaches to proportional joint torque control have

removed the open loop nature of previous controllers by using real-time joint torque estimates.

c. "Should a user respond defensively or adapt poorly, the system may enter vicious cycles with drifting and dangerous assistance. This was supported by the lack of statistical significance in muscle benefit compared to zero-torque condition (Supplementary Figure 12)." Supplementary Figure 12 shows the alternative approach was quite effective (~35% reduction in muscle activation, which is very similar to the proposed approach). Lack of statistical significance is more likely due to sample size here. Please update.

d. The exoskeleton torque of Gen2 in Supplementary Figure 13 seems very similar to the optimized torque. If possible, please provide more details of why Gen2 torque was intolerable.

e. "Formulating exoskeleton assistance by the proposed iterative tuning outperformed directly asserting a fixed portion of unassisted joint torque (Supplementary Figure 13)." This result was not statistically significant and the difference of 5% between the Gen2 and Optimized conditions is fairly small relative to other comparisons in this study. Please soften this statement accordingly.

f. Given the comments above, the remainder of the discussion comparing the proposed approach to proportional joint torque control should also be softened.

Reviewer #3

(Remarks to the Author)

The revised manuscript addressed all my comments. I suppose the current version of the manuscript can be accepted.

Reviewer #4

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Communications Engineering initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Reviewer #5

(Remarks to the Author)

I appreciate authors for their thorough revisions. I'm satisfied with the current manuscript, but I'd like to address my comment about the variable λ . I believe the authors interpreted my comment to mean they must include the variable k in their equations. However, I think it's better to remove k for improved readability. My comment was more about having a cost function with a set of variable coefficients. If you agree that λ is variable, then your cost function is also variable, meaning it changes slightly at each optimization step. This isn't intuitive because, during optimization, the cost function structure is typically kept constant, not variable with respect to the step.

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Response to the Reviewers

Manuscript #: COMMS-25-0240-T:

Interaction-based rapid heuristic optimization of exoskeleton assistance during walking

Jianyu Chen, Weihao Yin, Jianquan Ding, Jiaqi Han, Lihai Zhang, Jianda Han, Juanjuan Zhang

NOTE that:

- ◇ All reviewer comments are in **Sans Serif** font in **BLACK**.
- ◇ All author responses are in **Sans Serif** font in **BLUE**.
- ◇ All quotes of manuscript content are in **Roman** font, mostly in **BLACK**.
- ◇ All changes are highlighted in **MAROON** in the revised manuscript, including those quoted in this file.

ACKNOWLEDGEMENT

We wish to convey our sincere gratitude to all reviewers for carefully reading our manuscript and sharing insightful and constructive comments. These inputs have been greatly helpful in refining the presentation of this manuscript and will guide the directions and methodologies of our future research.

We have made careful revisions on the manuscript by respecting all the comments and suggestions. Details are in the subsequent parts of this document.

Reviewer 1 :

Overall Comments

This manuscript introduces a new method for human-in-the-loop exoskeleton assistance optimization using gradient descent based on real-time human joint moment estimates. This approach converges within a few minutes, which is much faster than previous methods, and the controller does not require spline parameters. While the authors' approach did significantly reduce user energy expenditure, the impact of this work is unclear unless the authors further clarify their results compared to prior work.

NOTE that:

- ◇ Reviewer comments in are **Sans Serif** font in **BLACK**.
- ◇ Author responses are in **Sans Serif** font in **BLUE**.
- ◇ Quotes of manuscript content are in **Roman** font, mostly in **BLACK**.
- ◇ Changes are highlighted in **MAROON** in the revised manuscript, including those quoted in this file.

Responses:

We thank the reviewer for carefully reading the manuscript and providing the following insightful comments. We have made revisions accordingly to improve the clarity of our presentation, including:

1. **Metabolic benefit comparison:** We have clarified that the metabolic benefit achieved by our method was comparable to the state-of-the-art (Zhang et al., 2017, Science; Slade et al., 2022, Nature).
2. **“Non-parametric” terminology:** We have revised the text to clarify that 'non-parametric' refers to the fact that no pre-design or parameterization of assistance was needed. We have further specified that the method used online heel-strike and gait timing detection, but required no explicit identification of the ambulation conditions.
3. **Advantage over biological moment application:** We have more clearly articulated the advantages of our method over the direct application of joint moments (as mentioned by the reviewer), by extended literature review, additional experiments, analysis and additional discussion. The key differentiators are:
 - An iterative process that enhances comfort, prevents stress responses, and promotes cooperative human-exoskeleton interaction to follow human intrinsic adaptation and optimization.
 - The presence of baseline unassisted joint torque in the tuning rule to provide stability and effectiveness.

We have also added comparison with a generic assistance proportional to baseline biological moments.

4. **Methodological details:** As suggested, we have added necessary experimental context to the **Abstract** and **Methods** to prevent ambiguity, e.g., the conditions under which results were obtained.
5. **Unilateral emulator justification:** We have justified the use of a unilateral exoskeleton emulator in the main study. This setup was chosen to facilitate a direct and accurate comparison with a state-of-the-art study (Zhang et al., 2017) since it closely mirrored their system. While our group did possess bilateral systems, Slade et al. (2022) used a more different platform. Nevertheless, the methods in [Zhang et al., 2017] and [Slade et al., 2022] are comparable in performance (though different in efficiency). We thus used [Zhang et al., 2017] as our primary performance benchmark and [Slade et al., 2022] for efficiency context.
6. **Test order justification:** We have added justification for condition testing order in validation: (NW-ZT-Gen-Opt-Opt-Gen-ZT-NW). This order was designed to minimize the potential bias from user familiarization and avoid interface disruptions from repeated attaching/detaching of the exoskeleton.
7. **Famliy-wise error rate control:** All reported P values from t-tests have been adjusted for famliy-wise error rate control using the Holm-Bonferroni correction.

We believe these revisions have helped to more clearly highlight the impact and contributions of our work:

- **State-of-the-Art performance:** The method achieves metabolic and muscular benefits comparable to those reported by state-of-the-art human-in-the-loop optimization (Zhang et al., 2017; Slade et al., 2022)—using a single, two-minute optimization process, without requiring separate tuning for each metric.
- **Rapid, closed-loop Optimization:** Our approach optimizes exoskeleton assistance in two minutes—sixteen times faster than the current state of the art—with no need for pre-defined assistance profiles, parameter tuning, or explicit identification of ambulation conditions.
- **Better safety, comfort and effectiveness than feedforward approaches:** Our method ensured instantaneous and cooperative human adaptation and made exoskeleton follow it with iterative tuning, real-time feedback and constraints.
- **A generalizable framework:** Our work suggests a framework for rapid optimization—comprising an instantaneously measurable interaction feedback, a reasonable tuning direction, and a direct feedback-to-parameter association—that can be applied to develop a family of similar methods.

Please check the point-by-point responses below.

Comments Group 1:

Impact/Claims: The author's make several claims about the optimization method presented in this work. I agree that their approach converges much faster than previous methods and shows promise for generalizing beyond level-ground, normal-speed walking; however, without adding more discussion, it's unclear how this work compares to state-of-the-art methods for metabolic cost optimization and multi-task exoskeleton control.

Responses:

We thank the reviewer for the following insightful comments.

- The work of Slade et al (Nature 2022) also introduced a method for rapidly optimizing user energy expenditure without the need for metabolic measurements. The authors correctly note that their work converges much faster than that of Slade et al, but it is potentially less effective. If so, please add discussion further detailing the trade-offs between these two methods.

Responses:

We thank the reviewer for raising this important point. In the original manuscript, we stated that the metabolic cost reduction achieved by our method, while statistically comparable, was “seemingly less” in mean value (20.4%) than that reported in [Zhang et al., 2017]. We agree that the phrasing “seemingly less” was misleading and have removed it.

Upon re-examination, we are confident that the metabolic benefit achieved is true and attribute the comparable reduction to the method's accomplishment on user comfort. By promoting co-operative human-exoskeleton interaction, the optimization yields assistance profiles that reduce metabolic demand. We have expanded on this explanation in the revised manuscript, specifically:

Original:

“The proposed method achieved comparable but seemingly less (n=10, 20.4% vs n=11, 24.2%; No statistically significant difference) energy consumption reduction compared to state-of-the-art when CMA-ES was used to directly minimize metabolism⁵. The reason was that the human feedback used, i.e., human torque during assisted walking, was a local mechanical variable. It was more correlated with local muscle activity rather than whole body energy cost. Nevertheless, metabolic cost is merely one of the many concerns for users walking with exoskeletons among others like comfort, local muscle activities, joint mobility and battery power consumption.”

Revised (Page 12, lines 313-320):

“The proposed method achieved comparable ($n = 10$, 20.4% vs $n = 11$, 24.2%; No statistically significant difference) energy consumption reduction to state-of-the-art metabolism-driven CMA-ES optimizations^{5,17}. Notably, this result was attained while optimizing for reduction in joint torque, a local mechanical correlate to muscle activity, rather than whole-body energy cost. This suggests that maintaining user comfort throughout the optimization process may inherently support metabolic efficiency. Furthermore, our approach achieved state-of-the-art reductions in both metabolic cost and muscle activity with a single, two-minute optimization process, whereas prior approaches required separate protocols to minimize each metric individually^{5,17}.”

- The authors state that their approach is non-parametric but should make it clear that this method is still dependent on a gait phase estimate and on known ambulation conditions (e.g., walking vs running, ground slope, walking speed).

Responses:

We have expanded discussion to clarify that 'non-parametric' refers to the fact that no pre-design and parameterization of assistance was needed. We have further specified that the method relies on the online detection of heel-strike events and gait timing, but does not require prior explicit identification of the ambulation conditions. Please check the specific revisions in Discussion:

Original:

“The proposed method has been easily and effectively deployed to new applications when gait conditions, assisted joints, assisting devices or user groups change. No more work than that when the participant changed was necessary. The ease was the result of the non-parametric formulation of assistance and its direct association with the real-time continuously evaluated feedback signal.”

Expanded 1 (Pages 12-13, lines 334-341):

“Easy deployment of the method to new scenarios arose from the non-parametric formulation, which required no pre-design and parameterization of exoskeleton assistance profiles. By deriving assistance directly from measured joint torques, the algorithm operated independently of ambulation conditions, eliminating the need for explicit gait identification. Transitioning to a new application scenario—whether due to changes in environment or user—simply required re-measuring baseline unassisted torque, identical to initial user calibration. This approach contrasts with traditional human-in-the-loop optimization methods^{5,17}, which necessitate extensive *a priori* research for specific joints, gait conditions, user populations, and exoskeleton devices.”

Expanded 2 (Page 16, lines 427-431):

“Meanwhile, the non-parametric nature of the assistance and the simplicity of the method enable computational demands to scale linearly with number of assisted joints, while optimization time remains unchanged. Thus, the method can be easily extended to multi-joint exoskeleton systems with only neglectable additional computing cost. ”

- The work of Gasparri et al (TNSRE 2019) and follow-up work by Dr. Lerner's group has shown similar metabolic benefits by imitating the biological ankle moment. Their approach may also generalize better since it is not dependent on gait phase or other ambulatory information. The authors should make it clear why the added complexity of their controller is advantageous.

Responses:

We thank the reviewer for raising this important point. We discussed only briefly regarding the mentioned issue in the old manuscript. The proposed method offers comfort, stability and guaranteed effectiveness, by an iterative gentle tuning process, a closed-loop optimization structure and proper constraints. We have more clearly articulated the advantages of our method over the direct application of joint moments, by expanded literature review, additional experiments, analysis and additional discussion subsection. The key differentiators are:

1. An iterative process that enhances comfort, prevents stress responses, and promotes cooperative human-exoskeleton interaction to follow human intrinsic adaptation and optimization.
2. The presence of baseline unassisted joint torque in the tuning rule to provide stability and effectiveness.

Besides, we have also added comparison with the a generic assistance proportional to baseline biological joint moments.

Specific revisions are below:

Original:

“Different from formulating assistance directly as functions of instant joint moments or muscle activities^{8,30,44}, continuous stride-wise tuning (Eq. (1)) facilitated iterative human adaptation to exoskeletons. Moreover, in less-likely cases when a participant felt defensive against the device, the presence of the nominal unassisted torque in the guide precluded potential vicious positive feedback cycles leading to drifting and dangerous assistances.”

Expanded literature review (Page 3, lines 66-75):

“In exoskeleton assistance planning, it is intuitive to imitate human biomechanics. Feed-forward approaches, which directly map instantaneous joint moment estimates or muscle activities to assistance torque^{8,10,30,44}, embody this straightforward principle. The

efficacy of such strategies depends on an efficient and cooperative human-machine interaction. However, their open-loop nature places the burden of achieving this synergy entirely on the user’s neuromuscular system. A user failure at reacting cooperatively and instantaneously may incur system instability and human danger. Recent study⁴⁵ introduced the Interaction Portrait metric to evaluate such interaction properties, underscoring the need for strategies that promote cooperative dynamics. For strategies based on human biomechanics, a proper closed-loop structure can potentially provide necessary environment and constraints to foster a stable and effective exoskeleton-assisting-human interface. ”

Additional results (Page 8, lines 193-215):

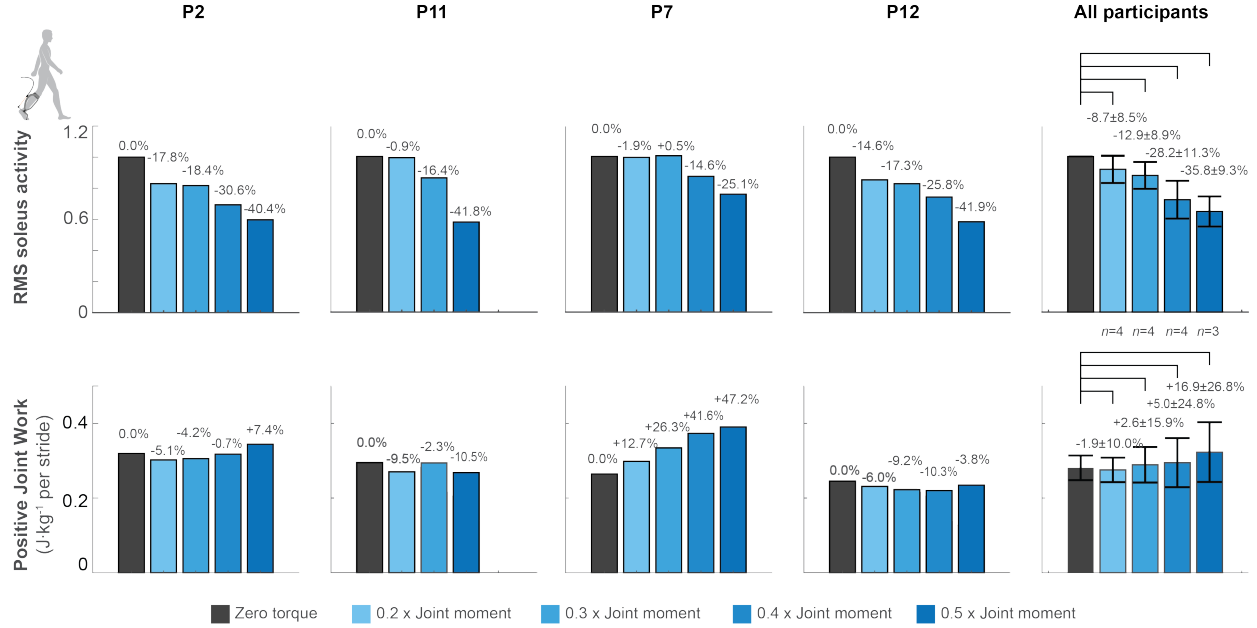
“

Exoskeleton assistance proportional to real-time assisted joint torque

We evaluated the performance of a feedforward strategy that applied a portion of real-time joint torque, with four different proportional gains ($K_f = [0.2 \ 0.3 \ 0.4 \ 0.5]$), on the unilateral ankle exoskeleton (Fig. 2b). Higher gains were associated with reduced voluntarily reported tolerability. 4 out of 6 participants (Supplementary Table 3) recruited could walk with more than half conditions and had data recorded, and only 3 went through all 4 gains. The reductions in soleus activity of the four conditions from zero-torque condition, were $8.7 \pm 8.5\%$ ($K_f = 0.2$, $n = 4$, paired t test, Holm-adjusted $P = 0.67$), $12.9 \pm 8.9\%$ ($K_f = 0.3$, $n = 4$, adjusted $P = 0.38$), $28.2 \pm 11.3\%$ ($K_f = 0.4$, $n = 4$, adjusted $P = 0.12$) and $35.8 \pm 9.3\%$ ($K_f = 0.5$, $n = 3$, adjusted $P = 0.15$) respectively (Supplementary Figure 12). Stride-wise positive ankle work increased by $-1.9 \pm 10.0\%$ ($K_f = 0.2$, $n = 4$, paired t test, adjusted $P = 1$), $2.6 \pm 15.9\%$ ($K_f = 0.3$, $n = 4$, paired t test, adjusted $P = 0.77$), $5.0 \pm 24.8\%$ ($K_f = 0.4$, $n = 4$, paired t test, adjusted $P = 1$) and $16.9 \pm 26.8\%$ ($K_f = 0.5$, $n = 3$, paired t test, adjusted $P = 1$).

Comparison to assistance proportional to unassisted joint torque

We also compared the proposed method to another generic assistance (Gen2), which asserted assistance proportional to the baseline joint torque during zero-torque mode (Supplementary Figure 13) at low torque, for 3 participants (Supplementary Table 4). Optimized condition demonstrated muscle activity reduction of $25.1 \pm 13.6\%$ ($n = 3$, 10.7% to 37.6% , adjusted $P = 0.85$), and $4.5 \pm 1.4\%$ ($n = 3$, 3.0% to 5.8% , adjusted $P = 0.70$), from zero-torque and Gen2 conditions respectively. Average peak asserted torques of Gen2 and optimized conditions were 0.391 and $0.410 \text{ Nm}\cdot\text{kg}^{-1}$ (Supplementary Figure 13.a). Two participants (P14, P2) voluntarily reported Gen2 condition to be severely more intolerable than the optimized. The lack of statistically significance in muscle benefit was likely due to low assistance torque and small sample size. ”



Supplementary Figure 12: Experiment results of asserting exoskeleton assistance torque proportional to real-time joint moment estimates. (Page S13, revised manuscript)

Experimental details for additional experiments (Page 28-29, lines 576-593):

“Six participants were recruited to evaluate the high-level exoskeleton planning strategy the asserts assistance proportional to the real-time estimates total joint torque, i.e.,

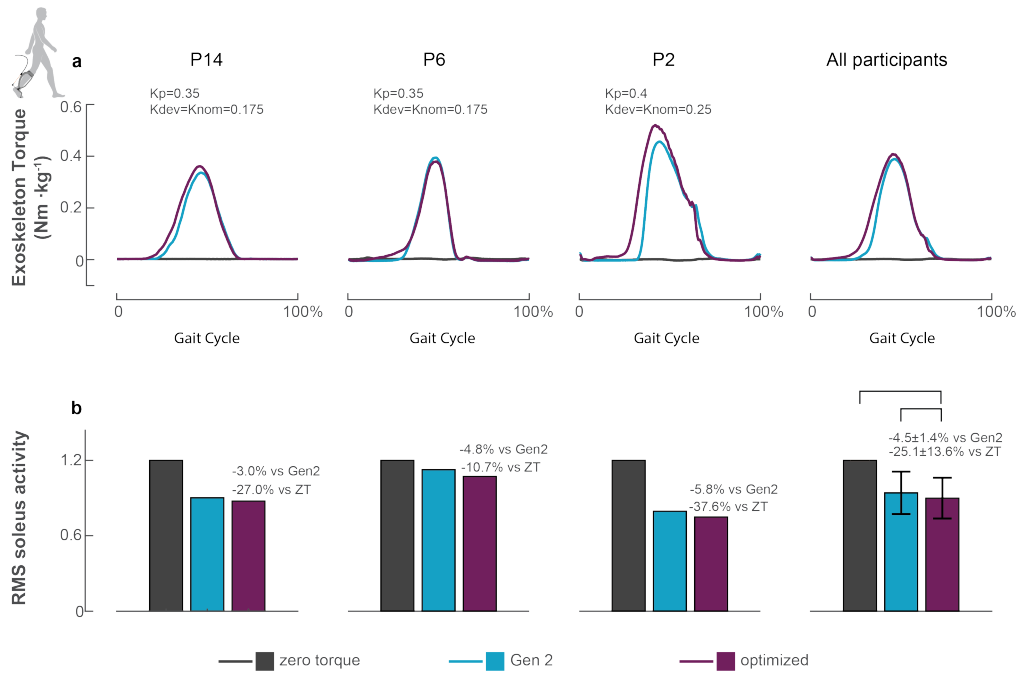
$$\tau_{exo} = K_f \cdot \tau_{joint} \quad (1)$$

where K_f is the proportional ratio, on the same unilateral ankle exoskeleton emulator as the main study. Two were unable to complete the protocol due to intolerance of the exoskeleton-induced instability. Consequently, data from four participants (all male, 24.3 ± 0.96 years, 1.83 ± 0.05 m, 72.8 ± 8.4 kg; Supplementary Table 3) were included in the analysis. Three participants (P2, P7, P12) completed trials at gains of $K_f = [0.2, 0.3, 0.4, 0.5]$. The fourth participant (P11) could not tolerate the $K_f = 0.5$ condition. ZT condition was included in validation as a reference. Conditions were tested in the order of ZT-0.2 τ_{joint} -0.3 τ_{joint} -0.4 τ_{joint} -0.5 τ_{joint} -0.5 τ_{joint} -0.4 τ_{joint} -0.3 τ_{joint} -0.2 τ_{joint} -ZT.

3 participants (all male, 24.7 ± 1.5 years, 1.79 ± 0.08 m, 76.3 ± 8.4 kg; Supplementary Table 4) were recruited for the comparison between the proposed method to the second generic assistance (Gen2), which asserted assistance proportional to the joint torque during zero-torque mode, i.e.,

$$\tau_{exo} = K_p \cdot \tau_{joint}^{ZT} \quad (2)$$

where K_p is a constant ratio. Tests were conducted on the same unilateral ankle exoskeleton emulator. While two participants (P14, P6) used relatively small pre-set gains



Supplementary Figure 13: Experimental comparison between the proposed method and asserting exoskeleton assistance torque proportional to zero-torque joint moment. Soleus activity of optimized assistance decreased by $25.1 \pm 13.6\%$ ($n = 3$, 10.7% to 37.6%, adjusted $P = 0.85$) from zero-torque mode, and by $4.5 \pm 1.4\%$ ($n = 3$, 3.0% to 5.8%, adjusted $P = 0.70$) from Gen2 mode. (Page S14, revised manuscript)

($K_p = 0.35$, $K_{dev} = K_{nom} = 0.175$), the third (P2) self-selected the maximum gains he was willing to tolerate for both conditions: $K_p = 0.4$ for Gen2 and $K_{dev} = K_{nom} = 0.5$ for the optimized case. ZT condition was included in validation for references. Conditions were tested in the order of ZT–Gen2–Opt–Opt–Gen2–ZT. ”

“

Performance relative to proportional-joint-torque approaches

The proposed update law (Eq. (1)) is characterized by an iterative tuning process and the steady-state convergence of exoskeleton torque to a portion of the steady-state assisted joint torque and one of the unassisted ($K_{dev} \cdot \tau_{joint} + K_{nom} \cdot \tau_{joint}^{ZT}$). Considering also that the method tries to minimize the difference between the two, this naturally lead to questions on its performance relative to strategies that direct asserting the same portions of real-time assisted joint torque ($\tau_{exo} = (K_{dev} + K_{nom}) \cdot \tau_{joint}$) or unassisted joint torque ($\tau_{exo} = (K_{dev} + K_{nom}) \cdot \tau_{joint}^{ZT}$).

The proposed iterative tuning method offers enhanced comfort, stability and effectiveness than feedforward approaches that formulates assistance directly from real-time joint moments or muscle activities^{8,10,30,44}. Both strategies posit positive correlations between exoskeleton torque and human biomechanics, and thus have performance dependent on the inner dynamics of how human body reacts to intervention. However, our method implements a closed-loop optimization, whereas feedforward paradigms operate in an open-loop manner. The proposed method (Eq. (1)) asserts minimal changes per stride and provides sufficient reaction time for human adaptation, which promotes comfort and cooperative responses. In contrast, feedforward approaches risk introducing abrupt intervention changes. Their efficacy hinges on the user’s ability to adapt cooperatively and instantaneously. Should a user respond defensively or adapt poorly, the system may enter vicious cycles with drifting and dangerous assistance. This was supported by the lack of statistical significance in muscle benefit compared to zero-torque condition (Supplementary Figure 12). The inter-personal variability, coupled with observed user intolerance, suggested that the proportional joint torque strategy was inherently unstable and sensitive to individual user dynamics and adaptation. Besides gradual adjustments, presence of the nominal unassisted torque in the tuning rule also inherently prevented undesirable human reactions from destabilizing the system. Therefore, the heuristic optimization is more robust and effective, particularly for users with gait impairments, ensuring both comfort and stability throughout adaptation.

Formulating exoskeleton assistance by the proposed iterative tuning outperformed directly asserting a fixed portion of unassisted joint torque (Supplementary Figure 13). The unassisted joint torque represents an equilibrium point resulting from the human user’s adaptation to the exoskeleton’s mechanical structure. Due to imperfect human-machine interface, exoskeleton actuation cannot fully replace muscle actuation. Therefore, assisted joint torque will inevitably deviate from the unassisted baseline as the system shifts to a new equilibrium under shared human–exoskeleton actuation (Fig. 4A). Different assistance profiles necessarily alter this equilibrium state. Within the result-

ing state space, one or several globally optimal equilibria exist. The iterative tuning basically provided an efficient pathway to converge to such optima. In contrast, applying a fixed portion of the unassisted torque fails to account for equilibrium shifts due to altered actuation modes and is therefore inherently suboptimal. This explains why participants found the Gen2 condition so uncomfortable, despite the low assistance torque and thus minimal difference in muscle benefit with optimized condition.

In summary, all three elements, i.e., the iterative process, the assisted joint torque, and the unassisted joint torque, are integral to the rule's effectiveness. The assisted torque enables closed-loop optimization that follows the user's internal adaptation. Iterative tuning nurtured cooperative human adaption. The assisted torque provides constraints and stability. ”

- Nit. The authors should clarify that the results presented in the Abstract are using an exoskeleton emulator (i.e., off-board actuation and power).

Responses:

Thank you for this point, we have clarified in the Abstract:

Original:

“Optimization of a unilateral ankle exoskeleton produced gentler and more energy-saving assistance (78.2% torque of state-of-the-art). ”

Revised (Page 1, lines 11-14):

“Optimization of a unilateral ankle exoskeleton with off-board actuation produced gentler assistance (78.2% torque) while reducing muscle activity by 36.8% and metabolic cost by 20.4% than no assistance, comparable to state-of-the-art.

Comments Group 2:

Methods: The methods presented in this manuscript are clear and rigorous. I have a few small comments for additional clarification.

Responses:

We thank the reviewer for the following detailed methodological comments.

- Please clarify why the majority of the study was conducted using only unilateral assistance? This makes it very hard to compare to the more recent and very relevant work of Slade et al. (Nature 2022). I would highly recommend additional metabolic testing using the bilateral ankle exoskeleton to improve the comparison to state-of-the-art methods.

Responses:

Thank you for raising this important question. We used unilateral instead of bilateral ankle exoskeleton in most of experiments due to two primary reasons:

1. Our exoskeleton emulator closely mirrors the system used in [Zhang et al., 2017], sharing the same motor model and a similar end-effector design, which enables a direct performance comparison. While a bilateral system was available used in generality tests, it differs more with the one used by Slade et al. (2022).
2. The method in [Slade et al., 2022] was an improvement over the implementation of [Zhang et al., 2017] on metabolism optimization, by using data-driven method to indirectly signal metabolic cost, without changing the underlying optimizer (CMA-ES). While faster, it was comparable in metabolic reduction with using [Zhang et al., 2017] to directly minimize metabolism. However, it considered and reported no muscle activity outcomes. In contrast, [Zhang et al., 2017] proposed the original framework that could directly optimize either metabolism or muscle activities, and included both type of experiments. Our proposed method, which achieved metabolic and muscular benefits simultaneously with a single two-minute tuning process, also had both metrics reported. Therefore, it is more reasonable to use [Zhang et al., 2017] served as the primary reference for optimization performance, whereas [Slade et al., 2022] provided a complementary benchmark for efficiency.

However, we do agree that extending this method to different devices, gait conditions, outdoor environments, and other assistance formulations represents an important direction for future research. We have expanded our discussion of these possibilities in the revised manuscript (see below for related revisions regarding testbed justification and future work).

Testbed choice justification (Page 4-5, lines 100-111):

“We tested the performance of the proposed method by optimizing the assistance of a unilateral single-degree-of-freedom plantarflexion ankle exoskeleton⁴⁷ during human walking (Fig. 2b). Experiments were conducted on a versatile emulator system⁴⁷ inspired by previous designs^{5,48} which allowed effective assistance updation, precise realization⁴⁹ and easy switching of exoskeleton end-effectors (Supplementary Figure 1). This system was chosen to facilitate easy comparison with a previous study⁵ directly minimizing human physiological measures with CMA-ES, which represents state-of-the-art assistance optimization performance. That study⁵ not only used an emulator system

that closely mirrored ours, with the same motor model and a similar end-effector design, but also reported both human metabolic and muscular benefit like ours. It thus served as the primary reference for optimization performance. Another key control study¹⁷ demonstrated comparable energy benefit with shorter optimization processes, which represents state-of-the-art optimization efficiency and served as the benchmark for convergence speed. ”

Future work discussion (Page 16-17, lines 433-453):

“The keys to the success of the proposed method, as discussed, included a) an instantaneously measurable interaction-related feedback, b) a reasonable tuning direction, and c) a continuous direct association between the feedback and the variable to be optimized. We do not claim the necessity to choose assisted joint torque as feedback, or unassisted joint torque as nominal guide, or assistance torque as variable, or updation rule based on absolute time in stride. Neither do we claim the necessity of matching data types between feedback and variable. Other interaction-related low-noise signals, such as interface impedance, power or energy, of the coupled system or a subsystem, might work as feedbacks. Sources other than experimental evaluations, such as simulations and prior studies, might be used to generate guides. Other forms of intervention to human, such as admittance, impedance, or motion profiles, might work as variables. Updation of variables from prior values might be based on relative time in stride, or kinetic information such as joint angles. Data-driven neural-network-based techniques might also be incorporated to enhance various parts of the process, e.g., joint torque estimation as in^{22,30}. These and more possibilities are yet to be explored and verified. Further studies of the current implementation are also beneficial. For example, the best learning rates and optimization durations might differ for various applications²⁶. Different relative weights between the nominal and the feedback terms in the guide might cause different behaviors and performances. **Effects of torque estimation errors are not yet rigorously investigated.** Insights of human-robot interaction and coupling mechanisms possibly revealed by the explicit model deserve deeper investigations. **Moreover, the assistance profiles achieved through optimization under fairly fixed conditions can be generalized to practical scenarios with varying speeds and individual strides⁵³.**”

- Please justify why the order of assistance conditions was fixed across participants during the double reversal experiments.

Responses:

We thank the reviewer for this important question. The fixed order of validation conditions, NW (Normal-Shoe)-ZT (Zero-Torque)-Gen (Generic Assistance)-Opt (Optimized Assistance)-Opt-Gen-ZT-NW, was intentionally designed to minimize two key confounding factors: learning

effects from the optimization process and disruptions from repeatedly attaching/detaching the exoskeleton. Our rationale is detailed below:

1. **Bookended normal walking (NW) conditions:** Placing the NW condition at both ends ensured a consistent human-device interface for all exoskeleton-involved conditions (ZT, Gen, Opt) in between. This design eliminated the need for multiple donning and doffing cycles.
2. **Centralized optimized (Opt) conditions:** The Opt condition was positioned centrally to maximize the time gap between the end of the optimization process and the validation of Opt condition. This design deliberately counteracts the potential advantage Opt could gain from short-term human adaptation and familiarity during the prior iterative tuning, ensuring a fairer comparison against other conditions.
3. **Order of ZT and Gen conditions:** Zero-torque (ZT) was tested before Generic Assistance (Gen) as it represents a more distinct departure from the Opt condition. This sequence further helped to “defamiliarize” the user from the Opt condition before testing the more similar Gen profile.

These rationales are also included in the Methods section of the revised manuscript (Page 28, lines 560-571):

“All conditions were tested in a double-reversal order of NW (normal-shoe walking)–ZT (zero-torque mode)–Gen (generic assistance mode)–Opt (optimized assistance mode)–Opt–Gen–ZT–NW. Placing the NW condition at both ends eliminated the need for multiple donning and doffing cycles. It ensured a consistent human-device interface for all exoskeleton-involved conditions (ZT, Gen, Opt) in between and thus a cleaner comparison. The Opt condition was positioned centrally to maximize the time gap between the end of the optimization process and the validation of Opt condition. This design deliberately counteracts the potential advantage Opt could gain from short-term human adaptation and familiarity during the prior iterative tuning, ensuring a fairer comparison against other conditions. ZT was tested before Gen as it represents a more distinct departure from the Opt condition. This sequence further helped to “defamiliarize” the user from the Opt condition before testing the more similar Gen profile. ”

Comments Group 3:

Statistics: The authors use paired t-tests for evaluating user outcomes across multiple pairwise comparisons. These tests should be updated with a method that corrects for the family-wise error rate (e.g., by applying a Bonferroni correction).

Responses:

We thank the reviewer for this valuable suggestion. All reported P -values from t tests, along with their corresponding interpretations, have been updated using the Holm–Bonferroni correction. This method was selected over Bonferroni correction since it was less conservative and more suitable for the dependent nature of our t tests. We are pleased to note that all original conclusions remain statistically supported. Adjusted P -values can be found in the Results section, and a description of the correction procedure has been added to the Methods section. Specific locations include:

Pages 5-7, lines 125 to 164:

“

Improvements on human muscle economy

Human muscle economy was significantly improved for all participants in validation (Fig. 3a,c; individual data are in Supplementary Figure 5). Optimized assistance reduced the activities of soleus muscle on the assisted side by $36.8 \pm 13.3\%$ (mean $\pm$ standard deviation, ranging from 22.0% to 57.1%) compared to zero-torque mode (Fig. 3a, $n = 10$, t test, **Holm-Bonferroni correction, adjusted $P = 1.1E-4$**), by $36.6 \pm 13.6\%$ (ranging from 21.0% to 61.5%) compared to normal-shoe mode (Fig. 3a, $n = 10$, t test, **adjusted $P = 1.1E-4$**), and by $15.0 \pm 7.0\%$ (ranging from 7.6% to 29.6%) compared to the generic condition (Fig. 3c, $n = 7$, t test, **adjusted $P = 3.0E-3$**). In comparison, with state-of-the-art approach using CMA-ES to directly minimize soleus activity for a similar exoskeleton, a 32-minute optimization process¹⁷ led to a decrease in soleus activity by $41\%^5$ (Fig. 3e, $n = 1$).

Improvements on human metabolic economy

Validation of the main study also demonstrated significant improvements on human metabolic economy through rapid optimization (Fig. 3b,d; individual data in Supplementary Figure 6). Optimized assistance reduced participants' net walking metabolic costs by $20.4 \pm 11.4\%$ (ranging from 7.8% to 39.1%) compared to zero-torque mode (Fig. 3b, $n = 10$, t test, **adjusted $P = 3.0E-3$**), by $19.7 \pm 10.3\%$ (ranging from 5.9% to 38.1%) compared to the normal-shoe mode (Fig. 3b, $n = 10$, t test, **adjusted $P = 3.0E-3$**), and by $13.7 \pm 9.8\%$ (ranging from 2.9% to 30.5%) compared to the generic condition (Fig. 3d, $n=7$, t test, **adjusted $P = 2.8E-2$**). In comparison, with state-of-the-art approach using CMA-ES to directly minimize metabolic costs⁵, 32-minute optimization processes¹⁷ produced net metabolic cost reduction of 24.2% (Fig. 3f, $n = 11$).

Improvements on human joint mechanics

Human joint mechanics were modified by the optimized assistance in validation for all participants (Fig. 4, Extended Data Figs. 7-10). Combined human-exoskeleton joint torque with

optimized assistance shifted a little from the unassisted torque along gait cycle (Fig. 4a), but rose obviously on the ankle angle axis and produced increased mechanical work input to human body (Fig. 4b). This aligned with the observation that the assisted ankle power curve shifted earlier in mid-stance, causing a decrease in negative power and an increase in positive power (Fig. 4c). With optimized assistance, average stride-wise ankle work increased by $25.4 \pm 15.7\%$ ($n = 10$, t test, **adjusted $P = 3.0E-3$**) compared to zero-torque mode, ranging from -2.1% to 47.0%, and by $36.0 \pm 25.6\%$ ($n = 10$, t test, **adjusted $P = 3.0E-3$**) compared to normal-shoe mode, ranging from 5.9% to 78.3% (Fig. 4d).

Customization of assistance torque profiles

The customization functionality of the method was demonstrated by the individualized optimized assistance profiles (peaked at $0.602 \pm 0.088 \text{ Nm kg}^{-1}$, $n = 10$, Fig. 3h, Supplementary Figure 7), each close to its guide at steady state (Fig. 4a), and lower than state-of-the-art⁵ (peaked at $0.770 \pm 0.086 \text{ Nm kg}^{-1}$; $n = 11$, two-tailed unpaired t test, **adjusted $P = 8.3E-4$**). Consequentially, work loops (Supplementary Figure 8), joint power (Supplementary Figure 9), corresponding improvements on human muscle (Supplementary Figure 5), metabolic (Supplementary Figure 6) and mechanical economies (Supplementary Figure 10) all varied among participants. ”

Pages 9-10, lines 244 to 247:

“..., the optimized assistance achieved comparable local muscle activity reduction ($n=10$, $36.8 \pm 13.3\%$ vs $n=1$, 41% ⁵, two-tailed unpaired t test, **adjusted $P = 0.77$**) and comparable walking metabolic cost reduction ($n=10$, 20.4% vs $n=11$, 24.2% ⁵, two-tailed unpaired t test, **adjusted $P = 0.74$**) from zero-torque mode. ”

Page 36, lines 755 to 768:

“ We used paired t -tests to compare the optimized assistance condition with generic assistance ($n = 7$), normal-shoe ($n = 10$), and zero-torque conditions ($n = 10$). The significant level was 0.05 for all analyses. No statistical analysis was performed for additional generality experiments of a small sample size ($n=1$). Two-tailed unpaired t -tests were used to compare the performance of our method demonstrated by the main study, **including optimized assistance parameters, metabolic cost reduction and muscle activities reduction**, with a control study⁵. In the proportional joint moment study, paired t -tests were used to compare each of the four conditions and zero-torque on stride-wise positive work and soleus activity, Holm-Bonferroni correction on P values was used to control family-wise error rate of type I errors. The 8 P values from paired t -tests of the main study were adjusted as a family. The 3 from unpaired t -tests between the optimized condition in our study and that in literature⁵ were adjusted as a second family. The 8 from paired t -tests of the proportional-moment

study were adjusted as a third family. The 2 from paired t -tests for the comparison between optimized condition and the generic assistance proportional to unassisted joint torque were adjusted as a fourth family. ”

Reviewer 3:

Overall Comments:

This study proposes a rapid heuristic optimization algorithm for exoskeleton-assisted walking, which uses joint torque as a feedback signal to optimize assistance by minimizing the combination of human efforts, exoskeleton inputs, and assistance-incurred biomechanical changes. This study achieves real-time biomechanics evaluation under different gaits, devices/joints, and outdoor environments while improving user comfort and reducing deployment costs. The manuscript is clear, organized, and rich in experiments, and the language is standardized.

Here, the reviewer lists some advice and comments to help improve the manuscript:

NOTE that:

- ◇ Reviewer comments are in **Sans Serif** font in **BLACK**.
- ◇ Author responses are in **Sans Serif** font in **BLUE**.
- ◇ Quotes of manuscript content are in **Roman** font, mostly in **BLACK**.
- ◇ Changes are highlighted in **MAROON** in the revised manuscript, including those quoted in this file.

Responses:

We are sincerely grateful for the reviewer's constructive comments. We have revised the manuscript accordingly, incorporating additional analyses and clarifications to address each point, as summarized below.

1. **Clarification of terminology and core methodological concept:** We have clarified key concepts, methodologies in multiple places through rephrasing, expanded literature review, additional experiments, and extended discussion.
2. **Strengthened methodological justification and analysis:** We have conducted a new analysis of ρ across the gait cycle for all participants, demonstrating how ρ varies along stride cycle, providing empirical insight into the optimization process. We have expanded the discussion in Discussion to directly address the feedback (τ_{human}) concern of the outdoor experiment.
3. **Comprehensive formatting and technical corrections:** We have fixed variable notation, equation numbering and reference formatting problems as mentioned and checked through the manuscript to clear similar issues.
4. **Enhanced discussion and future outlook:** The Discussion and Conclusion sections have been revised to more clearly articulate the core principles of our method (a measurable feedback signal,

a logical tuning direction, and a direct feedback-variable association) and to better distinguish our specific implementation from the generalizable framework it represents.

We believe the manuscript is now substantially stronger and hope that these revisions fully address all points raised. Please check the details below.

Comment 1

The manuscript claims realized a gradient descent optimization that minimized the combination of human efforts. It is a little bit misleading reader since human efforts are strongly relevant to muscle activity. It is highly recommended to clarify the key hypothesis of the work, and what the objective function and constraints of the proposed optimization method. In addition, maybe clarify the below sentence in the abstract “by minimizing human efforts while constraining exoskeleton assistance and joint mechanics”

Responses:

Thank you for your suggestion. We see the confusion about “human efforts”. We have revised related parts in Introduction, Abstract and Discussion to clarify terminology, hypotheses and claims, and also to distinguish between description of methodologies and the nature or mechanism underneath, through expanded literature review on human-machine interaction evaluation metrics and proportional joint moment strategies, additional experiments and discussion. specifically:

Abstract part:

From the original:

“ Here we present a method that optimizes assistance within 2 minutes, 16 times fast of state-of-the-art, by minimizing human efforts while constraining exoskeleton assistance and joint mechanics. ”

to the revised (Page 1, lines 10-11):

“ Here we present a method that optimizes assistance within 2 minutes, 16 times fast of state-of-the-art, **by effectively imitating human joint moment while ensuring stability.** ”

Introduction part:

From the original:

“ It realized a gradient descent optimization process⁴⁶ that minimized the combination of human efforts, exoskeleton inputs and assistance-incurred biomechanical changes (Eq. (2), Methods). ”

to the revised (Page 4, lines 88-91):

“It realized a gradient descent optimization process⁴⁶ that minimized the combination of human torque, exoskeleton inputs and assistance-incurred biomechanical changes (Eq. (2), Methods). It ensured safe, stable and cooperative human-exoskeleton interactions through the closed-loop framework and appropriate constraints.”

Additional discussion on method perspectives (Pages 9, lines 217 to 238):

“

Different perspectives on the proposed method

The proposed rapid optimization method (Eq. (1)) can be interpreted through several foundational perspectives, whose interplay gave rise to its different functional properties and performance outcomes.

The simple update law (Eq. (1)) constitutes an iterative learning process with a forgetting factor $(1-\alpha)$, which progressively adjusts exoskeleton torque toward a dynamic guide. The guide comprised the downscaled time-invariant unassisted joint torque, which served as a nominal destination, and the downscaled time-varying assisted joint torque, which introduced adaptive deviations from the nominal curve.

The online tuning approximates a gradient descent optimization⁴⁶ that minimizes a cost function comprising human torque, exoskeleton assistance and exoskeleton-induced changes of total joint torques (Eq. (2), Methods), in which the last objective is prioritized. As human and exoskeleton torques constitute the assisted joint torque, this formulation encouraged the maintenance of natural joint biomechanics while efficiently offloading muscular effort with minimal exoskeleton input.

Furthermore, the tuning rule forms a positive feedback loop between the exoskeleton torque and the real-time assisted joint torque with the positive gain (K_{dev} , Eq. (1)) set for the assisted torque in this study.

This is an exoskeleton optimization process that leverages human intrinsic motor optimization. The algorithm dynamically adjusts the assistance to track the assisted joint torque, which resulted from human adaptation to the exoskeleton’s intervention. By creating a structured environment that facilitated human-machine cooperation, it ensures that the assisted torque adapt optimally and be a reliable tracking target.”

Expanded discussion on method effectiveness (Pages 10-11, lines 262 to 280):

“The effectiveness of the proposed method in optimizing exoskeleton assistance was attributed to its nature as a closed-loop optimization strategy with appropriate objectives and constraints. The assisted joint torque, which comprised human and exoskeleton torques,

served as a feedback signal and included human in high-level control loop. Besides, assistance tuning with this method was approximately equivalent to a gradient descent optimization. Therefore, it achieved both “closed-loop” and “optimization”. However, the implementation of a human-in-the-loop optimization does not inherently guarantee user benefit. The feedback signal or objective function must be designed to correlate with physiologically meaningful human outcomes. Real-time assisted joint torque is the result of human optimal adaptation to gradually changing exoskeleton interventions. Consequently, using it as feedback meant a meaningful human-body-optimized tuning direction. On another note, the positive feedback loop between exoskeleton torque and assisted joint torque was purposely designed to encourage growth of exoskeleton torque, by exploiting the inherent diverging property of such loops, to produce meaningful assistance. In contrast, a negative feedback loop ($K_{dev} < 0$) would minimize the torque and cause the tuning process to fail. Crucially, the presence of the nominal guide (the assisted joint torque) constrained assistance divergence, ensuring system stability and preventing human injuries. On top of all these, user comfort throughout the optimization process prevented fight-or-flight responses and nurtured human-machine cooperation^{51,52}. It represented an important factor why the feedback, i.e., assisted joint torque, was optimally adapted and thus such a short process turned out so effective.”

Comment 2

2. The setting of the parameter ρ lacks an experimental basis. The paper assumes $\rho=0.05$, but the actual human adaptability may be more complicated. It is recommended to analyze the ρ value through experiments.

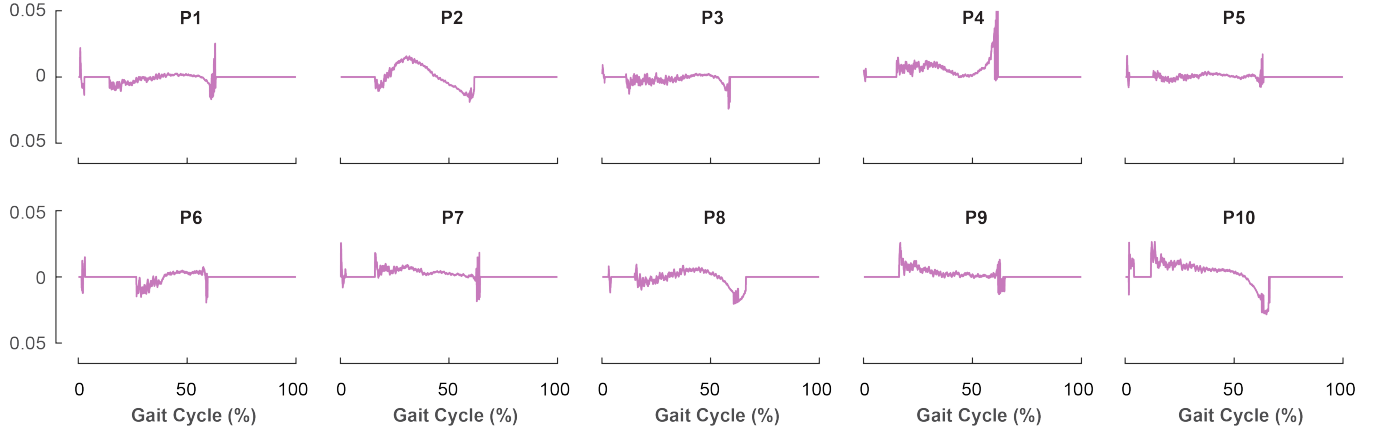
Responses:

We thank the reviewer for this insightful observation. We agree that the parameter ρ requires careful interpretation. In our methodological description, the value $\rho = 0.05$ was not an assumed constant but rather an illustrative example of a fixed value applied at a specific index k , the number of elapsed control cycles in the current stride. In fact, ρ was small number varying with k , and across participants (Supplementary Figure 14). We have clarified this point in the revised manuscript to better reflect the dynamic nature of the parameter. We also added discussion on the indication of ρ values during human-exoskeleton interaction.

Related revisions include (Pages 24-27, lines 474 to 529):

“ Consider a stride-wise cost function $J_{stride} = \sum_{k=1}^{StrideEnd} J(k)$, in which $J(k)$ stands for the cost function for index k within a gait cycle, formulated as

$$J(k) = \frac{1}{2}\lambda_1(k)\tau_{human}^2(k) + \frac{1}{2}\lambda_2(k)\tau_{exo}^2(k) + \frac{1}{2}\lambda_3(k)[\tau_{joint}(k) - \tau_{joint}^{ZT}(k)]^2. \quad (2)$$



Supplementary Figure 15: Estimated ρ value along the stride cycle averaged through optimization for all 10 participants of main experimental study. (Page S15, revised manuscript)

τ_{human} is the human biological joint moment, τ_{exo} is the exoskeleton assistive torque, τ_{joint} is the human-exoskeleton combined joint moment, τ_{joint}^{ZT} is the unassisted human joint torque, and $\lambda_1(k), \lambda_2(k), \lambda_3(k)$ are non-negative constants for index k . The partial derivative of the cost function with respect to τ_{exo} is

$$\begin{aligned} \frac{\partial J(k)}{\partial \tau_{exo}(k)} = & \lambda_1(k) \tau_{human}(k) \cdot \frac{\partial \tau_{human}(k)}{\partial \tau_{exo}(k)} + \lambda_2(k) \tau_{exo}(k) \\ & + \lambda_3(k) [\tau_{joint}(k) - \tau_{joint}^{ZT}(k)] \cdot \frac{\partial \tau_{joint}(k)}{\partial \tau_{exo}(k)}. \end{aligned} \quad (3)$$

Since $\tau_{joint}(k) = \tau_{human}(k) + \tau_{exo}(k)$,

$$\frac{\partial \tau_{human}(k)}{\partial \tau_{exo}(k)} = \frac{\partial \tau_{joint}(k)}{\partial \tau_{exo}(k)} - 1. \quad (4)$$

Let $\rho(k) = \frac{\partial \tau_{joint}(k)}{\partial \tau_{exo}(k)}$, we have

$$\begin{aligned} \frac{\partial J(k)}{\partial \tau_{exo}(k)} = & \lambda_1(k) \tau_{human}(k) \cdot [\rho(k) - 1] + \lambda_2(k) \tau_{exo}(k) + \lambda_3(k) [\tau_{joint}(k) - \tau_{joint}^{ZT}(k)] \cdot \rho(k) \\ = & [\lambda_2(k) - \lambda_1(k) \rho(k) + \lambda_1(k)] \tau_{exo}(k) + [\lambda_1(k) \rho(k) - \lambda_1(k)] \tau_{joint}(k) \\ & + \lambda_3(k) \rho(k) [\tau_{joint}(k) - \tau_{joint}^{ZT}(k)]. \end{aligned} \quad (5)$$

By gradient descent and the assumption that $\tau_{exo} = \tau_{des}$, with a learning rate of $\lambda(k)$,

$$\begin{aligned} \tau_{exo}(k, i + 1) = & \tau_{exo}(k, i) - \lambda(k) \cdot \frac{\partial J(k)}{\partial \tau_{exo}(k)} \\ = & \{1 - \lambda(k) [\lambda_2(k) - \lambda_1(k) \rho(k) + \lambda_1(k)]\} \tau_{exo}(k, i) \\ & + \lambda(k) \lambda_1(k) [1 - \rho(k)] \tau_{joint}(k, i) + \lambda(k) \lambda_3(k) \rho(k) [\tau_{joint}^{ZT}(k) - \tau_{joint}(k, i)]. \end{aligned} \quad (6)$$

Human locomotion is itself optimized and tends to maintain its original biomechanics as much as possible at the presence of external disturbances. Especially under gentle assistance tuning like the approach in this study, in which $\alpha = 0.025$ and $K_{nom} + K_{dev} < 1$, human feels rather comfortable and safe and will not overreact⁵¹, i.e., $|\rho| \ll 1$. Here, negative, zero and positive ρ values respectively indicates that muscle torque reduction is a bit more than, the same as and slightly less than exoskeleton input increase. In any of these cases, total joint torque is not largely affected while human effort is partially replaced by exoskeleton at an efficiency R (Eq. (10)) of about 100%.

$$R = \frac{-\partial\tau_{human}}{\partial\tau_{exo}} \times 100\% = 1 - \rho \quad (7)$$

Any exoskeleton intervention that causes more improvement of mobility than the increase of human efforts constitutes meaningful assistance. 100% R clearly represents one such instance. Meanwhile, the tendency to keep natural joint biomechanics, ensured by complex human dynamics, also means a larger coefficient for joint torque changes, λ_3 , relative to λ_1 and λ_2 , in the cost function.

The approach proposed in this study was equivalent to enforcing a small constant positive $\rho(k)$, and thus constant α , K_{nom} and K_{dev} values at index k for an optimization session. Rewriting Eq. (6), we got the assistance update algorithm in the format of Eq. (1) as below:

$$\begin{aligned} \tau_{exo}(k, i + 1) &= (1 - \alpha)\tau_{exo}(k, i) + \alpha(K_{dev} + K_{nom})\tau_{joint}(k) + \alpha K_{nom} [\tau_{joint}^{ZT}(k) - \tau_{joint}(k, i)] \\ &= (1 - \alpha)\tau_{exo}(k, i) + \alpha [K_{nom}\tau_{joint}^{ZT}(k) + K_{dev}\tau_{joint}(k, i)] \end{aligned} \quad (8)$$

in which

$$\begin{aligned} \alpha &= \frac{\lambda(k) [\lambda_2(k) - \lambda_1(k)\rho(k) + \lambda_1(k)]}{\lambda_1(k) [1 - \rho(k)]}, \\ K_{dev} + K_{nom} &= \frac{\lambda_1(k) [1 - \rho(k)]}{\lambda_2(k) - \lambda_1(k)\rho(k) + \lambda_1(k)} \in (0, 1), \\ K_{nom} &= \frac{\lambda_3(k)\rho(k)}{\lambda_2(k) - \lambda_1(k)\rho(k) + \lambda_1(k)} > 0. \end{aligned} \quad (9)$$

Analysis based on the cost function in Eq. (2) aligns with that based on the tuning rule in Eq. (1). Equal weights of nominal and feedback terms in tuning guide, i.e., $K_{nom} = K_{dev}$, together with a small $\rho(k)$, means a big $\lambda_3(k)$, which aligns with previous discussion that small $\rho(k)$ and big $\lambda_3(k)$ come as a pair. For example, $\lambda_3(k) = 9.5\lambda_1(k)$ when $\rho(k) = 0.05$. Meanwhile, smaller K_{nom} and K_{dev} values suggest larger $\lambda_2(k)$, i.e., more intention to keep exoskeleton assistance smaller. This aligned with the results that participants with smaller K_{nom} and K_{dev} had smaller peak optimized torque values (Supplementary Table 2 & Supplementary Figure 11).

*More on ρ , R and human-exoskeleton interaction behavior

Both $\rho = \frac{\partial \tau_{joint}}{\partial \tau_{exo}}$ and $R = -\frac{\partial \tau_{human}}{\partial \tau_{exo}}$ describe human body's reactions to exoskeleton input. They are governed by the internal physical and chemical dynamics of human body. The definition of ρ was introduced to design, by inverse dynamics, an exoskeleton torque tuning rule (Eq. (1)) that governs how the exoskeleton reacts to human actions, i.e., $\frac{\partial \tau_{exo}}{\partial \tau_{joint}}$ or $\frac{\partial \tau_{exo}}{\partial \tau_{human}}$. Therefore, the values of ρ solely without the knowledge of $\frac{\partial \tau_{exo}}{\partial \tau_{joint}}$, sometimes cannot fully portray the human-exoskeleton interaction behaviors.

When $|\rho| \ll 1$ as produced by the proposed method in this study, human effort is replaced by exoskeleton at an efficiency of $R \approx 100\%$. This qualifies as effective exoskeleton assistance while maintaining original mobility. In this region, $-1 \ll \rho < 0$, $\rho = 0$ and $0 < \rho \ll 1$ correspond to slight reduction, maintenance, and slight augmentation of the total joint torque, respectively.

Beyond the $|\rho| \ll 1$ region and discussion of this rapid heuristic optimization method, if $0 < \rho \leq 1$ ($0 \leq R < 100\%$), increase in exoskeleton torque causes decrease or no change in human torque. Total joint torque is thus augmented.

If $\rho > 1$, increase in exoskeleton torque will lead to increase in human torque, which means the user is resisting exoskeleton intervention. Although joint torque is further enlarged, this situation may incur instability and endanger the user, depending on the exoskeleton high level controller for input torque planning, i.e., $\frac{\partial \tau_{exo}}{\partial \tau_{joint}}$.

If $\rho < 0$ (i.e., $R > 100\%$), the user feels insecure and attempts to disengage or 'escape' from the exoskeleton. Human torque decreases more than exoskeleton torque increases, leading to a net reduction in total joint torque.

However, this analysis is about instant changes in total joint torque. To fully assess joint mobility and human-exoskeleton interaction modes, changes in joint torque and joint motion must be considered together over the entire gait cycle. ”

Comment 3

3. In the outdoor exoskeleton assistance optimization experiment, the feedback signal was changed from τ_{joint} to τ_{human} , but the impact of this replacement on the optimization was not verified. It is recommended that the effects of outdoor torque estimation error on exoskeleton assistance optimization be analyzed.

Responses:

We thank the reviewer for this insightful comment. We agree that rigorous analysis of torque estimation error is an important research direction, which we are actively pursuing. However, a direct comparison between mobile pressure insoles and accurate ground reaction measurement tools, e.g., instrumented treadmill or force plate, throughout the optimization process is not practical. A proper validation would require a dedicated study involving offline error characterization, optimization implementation with different sensors and algorithms, and systematic performance comparison—a substantial effort beyond the scope of this paper.

Here, we focus on demonstrating the effectiveness of a general rapid optimization framework characterized by “a) an instantaneously measurable interaction-related feedback, b) a reasonable tuning direction, and c) a continuous direct association between the feedback and the variable to be optimized.” (Page 16, lines 433-435). The successful implementation outdoors, using τ_{human} derived from pressure insoles instead of τ_{joint} , demonstrated the robustness of the framework. The fact that effective optimization was achieved, despite change of feedback variable and potential estimation errors, indicates that the method is tolerant to signal noise as long as the fundamental criteria (a-c) are satisfied. We have expanded our discussion in the Conclusion section to explicitly acknowledge this point and to frame the investigation of different sensors and estimation algorithms as a key future research direction. We appreciate the reviewer’s suggestion, which helps highlight both the robustness of our method and an interesting pathway for subsequent studies.

Related revisions include:

Additional discussion (Pages 13, lines 342-351):

“The method’s effectiveness when using ground reaction induced torque as joint torque estimates (τ_{joint} , Eq. (13)) demonstrated its robustness to estimation errors. In contrast, existing assistance planning based on joint moment usually employ complex estimation methods such as neural-network- or musculoskeletal-model-based ones^{8,10,30} for better accuracy. The proposed method, though, used only the ground reaction data from the instrumented treadmill and position data of several motion markers (Eq. (12)). This tolerance was further confirmed by the successful implementation on the mobile exoskeleton outdoors, where ground reactions were estimated using one-dimensional pressure insole readings (Eq. (16)) rather than six-dimensional treadmill data. Additionally, the substitution of total joint torque (τ_{joint}) with human torque (τ_{human}) in the algorithm (Eq. (16)) suggested the framework’s generalizability to alternative feedback modalities.”

Future works discussion (Pages 16-17, lines 433-453):

“The keys to the success of the proposed method, as discussed, included a) an instantaneously measurable interaction-related feedback, b) a reasonable tuning direction, and c) a continuous direct association between the feedback and the variable to be optimized. We do not claim the necessity to choose assisted joint torque as feedback, or unassisted joint torque

as nominal guide, or assistance torque as variable, or updation rule based on absolute time in stride. Neither do we claim the necessity of matching data types between feedback and variable. Other interaction-related low-noise signals, such as interface impedance, power or energy, of the coupled system or a subsystem, might work as feedbacks. Sources other than experimental evaluations, such as simulations and prior studies, might be used to generate guides. Other forms of intervention to human, such as admittance, impedance, or motion profiles, might work as variables. **Updation of variables from prior values might be based on relative time in stride, kinetic information such as joint angles, or other kinds of gait phase estimators.** Data-driven neural-network-based techniques might also be incorporated to enhance various parts of the process, e.g., joint torque estimation as in^{22,30}. These and more possibilities are yet to be explored and verified. Further studies of the current implementation are also beneficial. For example, the best learning rates and optimization durations might differ for various applications²⁶. Different relative weights between the nominal and the feedback terms in the guide might cause different behaviors and performances. **Effects of torque estimation errors are not yet rigorously investigated.** Insights of human-robot interaction and coupling mechanisms possibly revealed by the explicit model deserve deeper investigations. **Moreover, the assistance profiles achieved through optimization under fairly fixed conditions can be generalized to practical scenarios with varying speeds and individual strides⁵³.**

Comment 4

4. Modification of format:

Responses:

Thank you so much for carefully reading the manuscript and catching all these problems. We have made changes accordingly.

1) Variables should be uniformly italicized, and different variables should be represented by different symbols. For example, participant number n should be uniformly italicized. The symbols for the participant number and current stride number are both n , and the symbols for the joint maker and pressure reading are both P . It is recommended to distinguish them.

Responses: In the revised manuscript, we have:

- italicized all variables,
- kept participant number as n and changed current stride number from n to i ,
- change joint maker position from P to Pt and foot pressure reading for outdoor tests from P to Pr ,
- change t test probability value from p to P , and

– checked through the manuscript and cleared similar problems.

2) Many formulas in the paper are not numbered. It is recommended to number all formulas.

Responses:

We have numbered all formulas in the main and supplementary documents.

3) The reference format is unified. For example, the format of the first letter of the journal name should be uniformly represented.

Responses:

We have unified the format of all references and capitalized first letters of all key words in journal names.

Reviewer 4:

Overall Comments

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Communications Engineering program to promote peer review training and provide appropriate recognition to early career researchers who co-review manuscripts.

Responses:

We thank the reviewer for help reviewing our manuscript. We have made revisions according to comments of all the other reviewers point-by-point. Please check our revised manuscript. All changes are highlighted in **MAROON**.

Reviewer 5:

Overall Comments

This work presents an exoskeleton assistance strategy to reduce human muscular effort and metabolic cost. The controller torque dynamically converge to 30-50% of the net joint torque measured by force pleated or pressure insole. Using a portion of biological joint torque as the exoskeleton assistance torque is not novel. However, the dynamic convergence to the continuously measured net joint torque is interesting and considerable. Given that human tries to keep the net torque optimized and with very gradual changes in exoskeleton torque, we can assume the net torque is still optimized and therefore net torque is a good candidate for assistance. This is a novel perspective which is worthy of consideration. Moreover, the relation between this very simple approach and the way it could be considered as a gradient descend-based minimization of a cost function based on human and exoskeleton effort as well as deviation from the human un-assisted torque is interesting, which however needs to be explained better. My main concern about the paper is, however, lacks clarity and complex and sometimes vague language. I found it hard to understand the terminologies in the first encounter and I'll suggest some points to help. In general, I find this work valuable for the field.

Please NOTE that:

- ◇ Reviewer comments are in **Sans Serif** font in **BLACK**.
- ◇ Author responses are in **Sans Serif** font in **BLUE**.
- ◇ Quotes of manuscript content are in **Roman** font, mostly in **BLACK**.
- ◇ Changes are highlighted in **MAROON** in the revised manuscript, including those quoted in this file.

Responses:

We thank the reviewer for the thorough review and insightful comments, which have significantly improved the manuscript and deepened our analysis. We are gratified that the reviewer concurs with our focus on methodological parsimony and efficacy. Whereas the initial draft emphasized the conceptual nature of the approach for a broader audience, we have revised the manuscript to provide a more comprehensive and methodologically precise description, specifically:

1. **Expanded literature review:** We have expanded discussion about prior studies, e.g., on human-machine interaction metrics and feedforward assistance strategies, in Introduction, to improve contextual foundation.
2. **Extended discussion:** We have added analyses, in Introduction, of the framework's interpretability, optimization characteristics, convergence behavior, metabolic outcomes, generalizability, deployability, robustness, and comparative advantages over existing methods.

3. **Methodological justifications:** We have clarified rationale for experimental testbed, condition ordering, and interpretation of the parameter ρ in Methods.
4. **Multiple comparison correction:** We have applied Holm–Bonferroni correction to all reported P values of t tests with statistical significance ($P < 0.05$), in Results, to control family-wise error rate of type I errors.
5. **Additional experiments and data:** We conducted additional experiments to compare the proposed methods against feedforward strategies asserting assistance proportional to real-time joint torque and to unassisted joint torque. We also added additional analysis of ρ and gait time based on the main experimental data.
6. **Clarified comparison with feedforward methods:** The distinction between our method and feedforward strategies—which inject a predefined portion of the biological joint moment—has been specifically clarified through an expanded literature review, new experiments, and discussion.
7. **Improved clarity:** We have refined terminology, hypotheses, and claims throughout the manuscript.
8. **Formatting corrections:** We have standardized notation, equations, and references.

Please check below for our point-to-point responses.

Comment 1

1. The way I understand this method is that the exoskeleton controller exponentially smoothens toward a weighted average of zero assistance torque (initial torque recorded from the user) and the net torque recorder from the previous stride. This is very simple, and I think there is nothing wrong with a method being simple. If the exo intervention is slightly changing in each stride, then human will optimally adapt to the intervention and then using the net recording torque as the exo torque (average of course) will make sense. I think this is a strong point about the paper but is not transferred efficiently due to lack of clarity.

Responses:

Thank you so much for catching this insightful point. We have added or expanded our discussions from different perspectives, which included this suggested one, and their relationships with different aspects of the methods' functionalities and characteristics, specifically:

Page 9, lines 217-238:

“

Different perspectives on the proposed method

The proposed rapid optimization method (Eq. (1)) can be interpreted through several foundational perspectives, whose interplay gave rise to its different functional properties and performance outcomes.

The simple update law (Eq. (1)) constitutes an iterative learning process with a forgetting factor (α), which progressively adjusts exoskeleton torque toward a dynamic guide. The guide comprised the downscaled time-invariant unassisted joint torque, which served as a nominal destination, and the downscaled time-varying assisted joint torque, which introduced adaptive deviations from the nominal curve.

The online tuning approximates a gradient descent optimization⁴⁶ that minimizes a cost function comprising human torque, exoskeleton assistance and exoskeleton-induced changes of total joint torques (Eq. (2), Methods), in which the last objective is prioritized. As human and exoskeleton torques constitute the assisted joint torque, this formulation encouraged the maintenance of natural joint biomechanics while efficiently offloading muscular effort with minimal exoskeleton input.

Furthermore, the tuning rule forms a positive feedback loop between the exoskeleton torque and the real-time assisted joint torque with the positive gain (K_{dev} , Eq. (1)) set for the assisted torque in this study.

This is an exoskeleton optimization process that leverages human intrinsic motor optimization. The algorithm dynamically adjusts the assistance to track the assisted joint torque, which resulted from human adaptation to the exoskeleton’s intervention. By creating a structured environment that facilitated human-machine cooperation, it ensures that the assisted torque adapt optimally and be a reliable tracking target.”

Pages 10-11, lines 262-280:

“The effectiveness of the proposed method in optimizing exoskeleton assistance was attributed to its nature as a closed-loop optimization strategy with appropriate objectives and constraints. The assisted joint torque, which comprised human and exoskeleton torques, served as a feedback signal and included human in high-level control loop. Besides, assistance tuning with this method was approximately equivalent to a gradient descent optimization. Therefore, it achieved both “closed-loop” and “optimization”. However, the implementation of a human-in-the-loop optimization does not inherently guarantee user benefit. The feedback signal or objective function must be designed to correlate with physiologically meaningful human outcomes. Real-time assisted joint torque is the result of human optimal adaptation to gradually changing exoskeleton interventions. Consequently, using it as feedback meant a meaningful human-body-optimized tuning direction. On another note, the positive feedback

loop between exoskeleton torque and assisted joint torque was purposely designed to encourage growth of exoskeleton torque, by exploiting the inherent diverging property of such loops, to produce meaningful assistance. In contrast, a negative feedback loop ($K_{dev} < 0$) would minimize the torque and cause the tuning process to fail. Crucially, the presence of the nominal guide (the assisted joint torque) constrained assistance divergence, ensuring system stability and preventing human injuries. On top of all these, user comfort throughout the optimization process prevented fight-or-flight responses and nurtured human-machine cooperation^{51,52}. It represented an important factor why the feedback, i.e., assisted joint torque, was optimally adapted and thus such a short process turned out so effective. ”

Comment 2

2. Given that K_{nom} and K_{dev} are equal and between 0.3 and 0.5 according to Supplementary Table 2 , then the averaging process is supposed to track 30-50% of the average torques of the last stride and no-assisted walking. Supplementary Figure8 supports this. I think such design (that the exo will converge to a certain amount of torque) should be clarified not mistaken with something that is the output of optimization.

Responses:

Thank you for raising this point. We have added states when discussing the optimized assistance to clarify this in the revised manuscript (Pages 11-12, lines 296 - 308):

“The comfortable optimization produced comfortable optimized assistance through different optimization routes and learning rates (Fig. 4a, Supplementary Figure 6). The assistance peak torque was lower compared to literature⁵. Moreover, the resulted optimized assisted joint torque deviated relatively little from the unassisted one along the axis of tuning (i.e., time in stride for this study, Fig. 4a), while exerting significantly more mechanical power (Fig. 4b-d). This was attributed to the tuning algorithm which partially minimized the difference between assisted and unassisted joint torques (Eq. (2)). Moreover, the algorithm determined that the optimized assistance converged to the steady-state guides (Fig. 4A, Supplementary Figure 7 and Supplementary Table 2) made of the downscaled optimized assisted and unassisted total joint torques ($K_{dev}\tau_{joint} + K_{nom}\tau_{joint}^{ZT}$). The close adjacency of these two torque profiles also positioned the final assistance around $K_{dev} + K_{nom}$ times the unassisted one. This outcome was deliberate, achieved through participant-selected guide gains (K_{nom} , K_{dev}), with the principal optimization results manifesting as deviations from the designed nominal profile ($(K_{dev} + K_{nom})\tau_{joint}^{ZT}$). ”

Comment 3

3. The gradient descend optimization equivalency of the simple averaging method is interesting, I encourage authors to clarify few points: 1) given that $\rho(k)$ is variable and k_{nom} and k_{dev} are fixed, it means that $\lambda_{1,2,3}$ are variable with respect to k which is not considered in Eq.2.

Responses:

We thank the reviewer for catching this. It is true that $\lambda_{1,2,3}$ are all variables dependent on index k , just like $\rho(k)$. We have clarify this in the revised manuscript by changing all λ_x to $\lambda_x(k)$ and adding explanations (Page 24-26, lines 474 to 505):

“ Consider a stride-wise cost function $J_{stride} = \sum_{k=1}^{StrideEnd} J(k)$, in which $J(k)$ stands for the cost function for index k within a gait cycle, formulated as

$$J(k) = \frac{1}{2}\lambda_1(k)\tau_{human}^2(k) + \frac{1}{2}\lambda_2(k)\tau_{exo}^2(k) + \frac{1}{2}\lambda_3(k)[\tau_{joint}(k) - \tau_{joint}^{ZT}(k)]^2. \quad (2)$$

τ_{human} is the human biological joint moment, τ_{exo} is the exoskeleton assistive torque, τ_{joint} is the human-exoskeleton combined joint moment, τ_{joint}^{ZT} is the unassisted human joint torque, and $\lambda_1(k), \lambda_2(k), \lambda_3(k)$ are non-negative constants for index k . The partial derivative of the cost function with respect to τ_{exo} is

$$\begin{aligned} \frac{\partial J(k)}{\partial \tau_{exo}(k)} &= \lambda_1(k)\tau_{human}(k) \cdot \frac{\partial \tau_{human}(k)}{\partial \tau_{exo}(k)} + \lambda_2(k)\tau_{exo}(k) \\ &\quad + \lambda_3(k) [\tau_{joint}(k) - \tau_{joint}^{ZT}(k)] \cdot \frac{\partial \tau_{joint}(k)}{\partial \tau_{exo}(k)}. \end{aligned} \quad (3)$$

Since $\tau_{joint}(k) = \tau_{human}(k) + \tau_{exo}(k)$,

$$\frac{\partial \tau_{human}(k)}{\partial \tau_{exo}(k)} = \frac{\partial \tau_{joint}(k)}{\partial \tau_{exo}(k)} - 1. \quad (4)$$

Let $\rho(k) = \frac{\partial \tau_{joint}(k)}{\partial \tau_{exo}(k)}$, we have

$$\begin{aligned} \frac{\partial J(k)}{\partial \tau_{exo}(k)} &= \lambda_1(k)\tau_{human}(k) \cdot [\rho(k) - 1] + \lambda_2(k)\tau_{exo}(k) + \lambda_3(k) [\tau_{joint}(k) - \tau_{joint}^{ZT}(k)] \cdot \rho(k) \\ &= [\lambda_2(k) - \lambda_1(k)\rho(k) + \lambda_1(k)] \tau_{exo}(k) + [\lambda_1(k)\rho(k) - \lambda_1(k)] \tau_{joint}(k) \\ &\quad + \lambda_3(k)\rho(k) [\tau_{joint}(k) - \tau_{joint}^{ZT}(k)]. \end{aligned} \quad (5)$$

By gradient descent and the assumption that $\tau_{exo} = \tau_{des}$, with a learning rate of $\lambda(k)$,

$$\begin{aligned}\tau_{exo}(k, i+1) &= \tau_{exo}(k, i) - \lambda(k) \cdot \frac{\partial J(k)}{\partial \tau_{exo}(k)} \\ &= \{1 - \lambda(k) [\lambda_2(k) - \lambda_1(k)\rho(k) + \lambda_1(k)]\} \tau_{exo}(k, i) \\ &\quad + \lambda(k) \lambda_1(k) [1 - \rho(k)] \tau_{joint}(k, i) + \lambda(k) \lambda_3(k) \rho(k) [\tau_{joint}^{ZT}(k) - \tau_{joint}(k, i)].\end{aligned}\tag{6}$$

Human locomotion is itself optimized and tends to maintain its original biomechanics as much as possible at the presence of external disturbances. Especially under gentle assistance tuning like the approach in this study, in which $\alpha = 0.025$ and $K_{nom} + K_{dev} < 1$, human feels rather comfortable and safe and will not overreact⁵¹, i.e., $|\rho| \ll 1$. Here, negative, zero and positive ρ values respectively indicates that muscle torque reduction is a bit more than, the same as and slightly less than exoskeleton input increase. In any of these cases, total joint torque is not largely affected while human effort is partially replaced by exoskeleton at an efficiency R (Eq. (10)) of about 100%.

$$R = \frac{-\partial \tau_{human}}{\partial \tau_{exo}} \times 100\% = 1 - \rho\tag{7}$$

Any exoskeleton intervention that causes more improvement of mobility than the increase of human efforts constitutes meaningful assistance. 100% R clearly represents one such instance. Meanwhile, the tendency to keep natural joint biomechanics, ensured by complex human dynamics, also means a larger coefficient for joint torque changes, λ_3 , relative to λ_1 and λ_2 , in the cost function.

The approach proposed in this study was equivalent to enforcing a small constant positive $\rho(k)$, and thus constant α , K_{nom} and K_{dev} values at index k for an optimization session. Rewriting Eq. (6), we got the assistance update algorithm in the format of Eq. (1) as below:

$$\begin{aligned}\tau_{exo}(k, i+1) &= (1 - \alpha) \tau_{exo}(k, i) + \alpha (K_{dev} + K_{nom}) \tau_{joint}(k) + \alpha K_{nom} [\tau_{joint}^{ZT}(k) - \tau_{joint}(k, i)] \\ &= (1 - \alpha) \tau_{exo}(k, i) + \alpha [K_{nom} \tau_{joint}^{ZT}(k) + K_{dev} \tau_{joint}(k, i)]\end{aligned}\tag{8}$$

in which

$$\begin{aligned}\alpha &= \lambda(k) [\lambda_2(k) - \lambda_1(k)\rho(k) + \lambda_1(k)], \\ K_{dev} + K_{nom} &= \frac{\lambda_1(k) [1 - \rho(k)]}{\lambda_2(k) - \lambda_1(k)\rho(k) + \lambda_1(k)} \in (0, 1), \\ K_{nom} &= \frac{\lambda_3(k)\rho(k)}{\lambda_2(k) - \lambda_1(k)\rho(k) + \lambda_1(k)} > 0.\end{aligned}\tag{9}$$

Analysis based on the cost function in Eq. (2) aligns with that based on the tuning rule in Eq. (1). Equal weights of nominal and feedback terms in tuning guide, i.e., $K_{nom} = K_{dev}$, together with a small $\rho(k)$, means a big $\lambda_3(k)$, which aligns with previous discussion that small $\rho(k)$ and big $\lambda_3(k)$ come as a pair. For example, $\lambda_3(k) = 9.5\lambda_1(k)$ when $\rho(k) = 0.05$. Meanwhile, smaller K_{nom} and K_{dev} values suggest larger $\lambda_2(k)$, i.e., more intention

to keep exoskeleton assistance smaller. This aligned with the results that participants with smaller K_{nom} and K_{dev} had smaller peak optimized torque values (Supplementary Table 2 & Supplementary Figure 11). ”

Comment 4

4. One may ask what happens if you just apply 30-50 percent of zero-torque walking to the user (feedforward assistance) without exponential smoothing? Such comparison would be interesting and shows which of the human biological torques or the gradual update of the controller are more important.

Responses:

We thank the reviewer for this insightful suggestion. This comment is closely linked to Comment 6, as both pertain to strategies that define exoskeleton assistance as a proportional share of joint moment.

To provide context, our method iteratively tunes exoskeleton assistance using the rule:

$$\tau_{exo}(k, i + 1) = (1 - \alpha)\tau_{exo}(k, i) + \alpha[(K_{dev} \cdot \tau_{joint}(k, i) + K_{nom} \cdot \tau_{joint}^{ZT}(k, i)].$$

The apparent features of this rule include an iterative tuning process and the steady-state convergence of exoskeleton torque to $(K_{dev} \cdot \tau_{joint}(k) + K_{nom}) \cdot \tau_{joint}^{ZT}(k)$. These properties motivated the reviewer's questions in comment 4 and 6, which we synthesize as follows:

- (1) Which is more critical to the method's success: the iterative tuning process or the baseline reference τ_{joint}^{ZT} ? (Comment 4)
- (2) How does the performance of the proposed method compare to a feedforward approach applying assistance proportional to unassisted joint torque at zero-torque mode (Comment 4):

$$\tau_{exo} = (K_{dev} + K_{nom}) \cdot \tau_{joint}^{ZT}$$

- (3) How does the proposed method compare to a feedforward approach that applying assistance proportional to the real-time assisted joint torque (Comment 6):

$$\tau_{exo} = (K_{dev} + K_{nom}) \cdot \tau_{joint}$$

- (4) What are the functional roles of (a) the iterative process, (b) real-time assisted joint torque τ_{joint} , and (c) unassisted joint torque during zero-torque walking τ_{joint}^{ZT} ?

In brief, all three components (a)-(c) are integral to the method's effectiveness. The assisted joint torque (τ_{joint}) provides real-time feedback, enabling closed-loop optimization that follows the user's

internal adaptive process. The iterative tuning ensures instantaneous, cooperative and gradual human adaption to intervention. The unassisted joint torque (τ_{joint}^{ZT}) provides a stabilizing baseline, constraining the assistance to a physiologically plausible range.

To address these questions thoroughly, we have conducted new experiments and significantly expanded the comparative analysis of these assistance strategies in the Introduction and Discussion sections, specifically:

Original:

“Different from formulating assistance directly as functions of instant joint moments or muscle activities^{8,30,44}, continuous stride-wise tuning (Eq. (1)) facilitated iterative human adaptation to exoskeletons. Moreover, in less-likely cases when a participant felt defensive against the device, the presence of the nominal unassisted torque in the guide precluded potential vicious positive feedback cycles leading to drifting and dangerous assistances.”

Expanded literature review (Page 3, lines 66-75):

“In exoskeleton assistance planning, it is intuitive to imitate human biomechanics. Feed-forward approaches, which directly map instantaneous joint moment estimates or muscle activities to assistance torque^{8,10,30,44}, embody this straightforward principle. The efficacy of such strategies depends on an efficient and cooperative human-machine interaction. However, their open-loop nature places the burden of achieving this synergy entirely on the user’s neuromuscular system. A user failure at reacting cooperatively and instantaneously may incur system instability and human danger. Recent study⁴⁵ introduced the Interaction Portrait metric to evaluate such interaction properties, underscoring the need for strategies that promote cooperative dynamics. For strategies based on human biomechanics, a proper closed-loop structure can potentially provide necessary environment and constraints to foster a stable and effective exoskeleton-assisting-human interface. ”

Additional results (Page 8, lines 193-215):

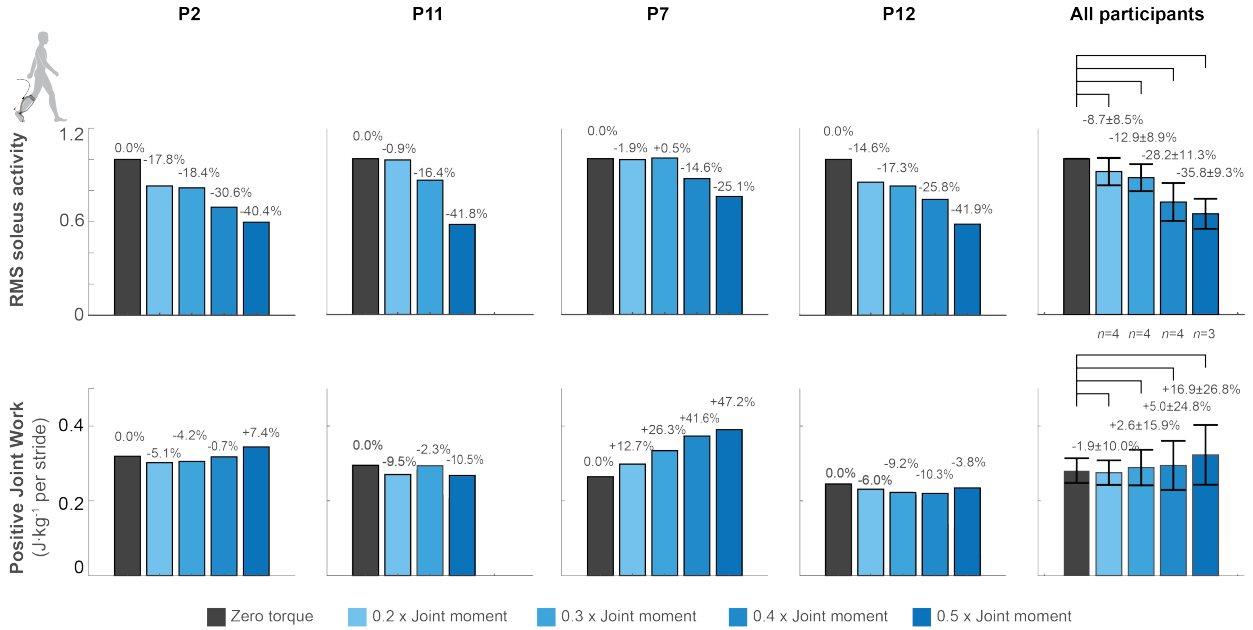
“

Exoskeleton assistance proportional to real-time assisted joint torque

We evaluated the performance of a feedforward strategy that applied a portion of real-time joint torque, with four different proportional gains ([0.2 0.3 0.4 0.5]), on the unilateral ankle exoskeleton (Fig. 2b). Higher gains were associated with reduced tolerability. 4 out of 6 participants (Supplementary Table 3) recruited could walk with more than half conditions and had data recorded, and only 3 went through all 4 gains. The reductions in soleus activity of the four conditions from zero-torque condition, were $8.0 \pm 9.0\%$ ($K_f = 0.2$, $n = 4$, paired t test, adjusted $P = 0.18$), $13.3 \pm 8.6\%$ ($K_f = 0.3$, $n = 4$, adjusted $P = 0.11$), $30.0 \pm 12.0\%$ ($K_f = 0.4$, $n = 4$, adjusted $P = 0.062$) and $37.7 \pm 8.6\%$ ($K_f = 0.5$, $n = 3$, adjusted $P = 0.062$) respectively (Supplementary Figure 12).

Comparison to assistance proportional to unassisted joint torque

We also compared the proposed method to another generic assistance (Gen2), which asserted assistance proportional to the baseline joint torque during zero-torque mode (Supplementary Figure 13) at low torque, for 3 participants (Supplementary Table 4). Optimized condition demonstrated muscle activity reduction of $25.1 \pm 13.6\%$ ($n = 3$, 10.7% to 37.6%, adjusted $P = 0.85$), and $4.5 \pm 1.4\%$ ($n = 3$, 3.0% to 5.8%, adjusted $P = 0.70$), from zero-torque and Gen2 conditions respectively. Average peak asserted torques of Gen2 and optimized conditions were 0.391 and 0.410 $\text{Nm}\cdot\text{kg}^{-1}$ (Supplementary Figure 13.a). Two participants (P14, P2) voluntarily reported Gen2 condition to be severely more intolerable than the optimized. The lack of statistically significance in muscle benefit was likely due to low assistance torque and small sample size. ”



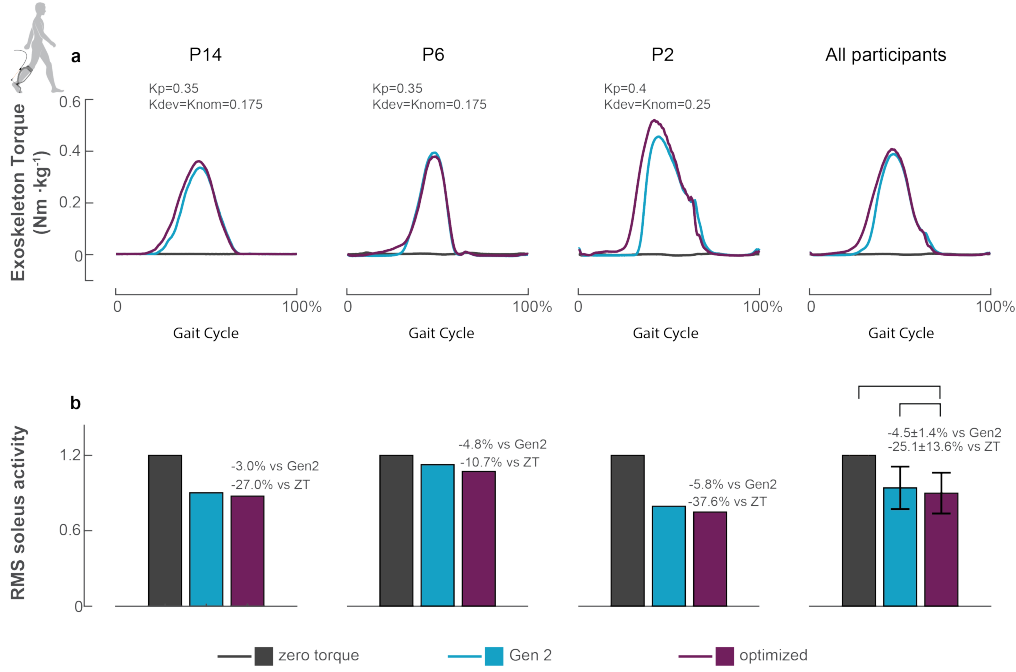
Supplementary Figure 12: Experiment results of asserting exoskeleton assistance torque proportional to real-time joint moment estimates. (Page S13, revised manuscript)

Experimental details for additional experiments (Pages 28-29, lines 576-593):

“Six participants were recruited to evaluate the high-level exoskeleton planning strategy the asserts assistance proportional to the real-time estimates total joint torque, i.e.,

$$\tau_{exo} = K_f \cdot \tau_{joint} \quad (10)$$

where K_f is the proportional ratio, on the same unilateral ankle exoskeleton emulator as the main study. Two were unable to complete the protocol due to intolerance of the exoskeleton-induced instability. Consequently, data from four participants (all male, 24.3 ± 0.96 years, 1.83 ± 0.05 m, 72.8 ± 8.4 kg; Supplementary Table 3) were included in the analysis. Three



Supplementary Figure 13: Experimental comparison between the proposed method and asserting exoskeleton assistance torque proportional to zero-torque joint moment. Soleus activity of optimized assistance decreased by $25.1 \pm 13.6\%$ ($n = 3$, 10.7% to 37.6%, adjusted $P = 0.85$) from zero-torque mode, and by $4.5 \pm 1.4\%$ ($n = 3$, 3.0% to 5.8%, adjusted $P = 0.70$) from Gen2 mode. (Page S14, revised manuscript)

participants (P2, P7, P12) completed trials at gains of $K_f = [0.2, 0.3, 0.4, 0.5]$. The fourth participant (P11) could not tolerate the $K_f = 0.5$ condition. ZT condition was included in validation as a reference. Conditions were tested in the order of ZT– $0.2\tau_{joint}$ – $0.3\tau_{joint}$ – $0.4\tau_{joint}$ – $0.5\tau_{joint}$ – $0.5\tau_{joint}$ – $0.4\tau_{joint}$ – $0.3\tau_{joint}$ – $0.2\tau_{joint}$ –ZT.

3 participants (all male, 24.7 ± 1.5 years, 1.79 ± 0.08 m, 76.3 ± 8.4 kg; Supplementary Table 4) were recruited for the comparison between the proposed method to the second generic assistance (Gen2), which asserted assistance proportional to the joint torque during zero-torque mode, i.e.,

$$\tau_{exo} = K_p \cdot \tau_{joint}^{ZT} \quad (11)$$

where K_p is a constant ratio. Tests were conducted on the same unilateral ankle exoskeleton emulator. While two participants (P14, P6) used relatively small pre-set gains ($K_p = 0.35$, $K_{dev} = K_{nom} = 0.175$), the third (P2) self-selected the maximum gains he was willing to tolerate for both conditions: $K_p = 0.4$ for Gen2 and $K_{dev} = K_{nom} = 0.5$ for the optimized case. ZT condition was included in validation for references. Conditions were tested in the order of ZT–Gen2–Opt–Opt–Gen2–ZT. ”

Additional discussion (Pages 13-14, lines 352-393):

“

Performance relative to proportional-joint-torque approaches

The proposed update law (Eq. (1)) is characterized by an iterative tuning process and the steady-state convergence of exoskeleton torque to a portion of the steady-state assisted joint torque and one of the unassisted ($K_{dev} \cdot \tau_{joint} + K_{nom} \cdot \tau_{joint}^{ZT}$). Considering also that the method tries to minimize the difference between the two, this naturally lead to questions on its performance relative to strategies that direct asserting the same portions of real-time assisted joint torque ($\tau_{exo} = (K_{dev} + K_{nom}) \cdot \tau_{joint}$) or unassisted joint torque ($\tau_{exo} = (K_{dev} + K_{nom}) \cdot \tau_{joint}^{ZT}$).

The proposed iterative tuning method offers enhanced comfort, stability and effectiveness than feedforward approaches that formulates assistance directly from real-time joint moments or muscle activities^{8,10,30,44}. Both strategies posit positive correlations between exoskeleton torque and human biomechanics, and thus have performance dependent on the inner dynamics of how human body reacts to intervention. However, our method implements a closed-loop optimization, whereas feedforward paradigms operate in an open-loop manner. The proposed method (Eq. (1)) asserts minimal changes per stride and provides sufficient reaction time for human adaptation, which promotes comfort and cooperative responses. In contrast, feedforward approaches risk introducing abrupt intervention changes. Their efficacy hinges on the user’s ability to adapt cooperatively and instantaneously. Should a user respond defensively or adapt poorly, the system may enter vicious cycles with drifting and dangerous assistance. This was supported by the lack of statistical significance in muscle benefit compared to zero-torque condition (Supplementary Figure 12). The inter-personal variability, coupled with observed user intolerance, suggested that the proportional joint torque strategy was inherently unstable and sensitive to individual user dynamics and adaptation. Besides gradual adjustments, presence of the nominal unassisted torque in the tuning rule also inherently prevented undesirable human reactions from destabilizing the system. Therefore, the heuristic optimization is more robust and effective, particularly for users with gait impairments, ensuring both comfort and stability throughout adaptation.

Formulating exoskeleton assistance by the proposed iterative tuning outperformed directly asserting a fixed portion of unassisted joint torque (Supplementary Figure 13). The unassisted joint torque represents an equilibrium point resulting from the human user’s adaptation to the exoskeleton’s mechanical structure. Due to imperfect human-machine interface, exoskeleton actuation cannot fully replace muscle actuation. Therefore, assisted joint torque will inevitably deviate from the unassisted baseline as the system shifts to a new equilibrium under shared human–exoskeleton actuation (Fig. 4A). Different assistance profiles necessarily alter this equilibrium state. Within the resulting state space, one or several globally optimal equilibria exist. The iterative tuning basically provided an efficient pathway to converge to such optima. In contrast, applying a fixed portion of the unassisted torque fails to account

for equilibrium shifts due to altered actuation modes and is therefore inherently suboptimal. This explains why participants found the Gen2 condition so uncomfortable, despite the low assistance torque and thus minimal difference in muscle benefit with optimized condition.

In summary, all three elements, i.e., the iterative process, the assisted joint torque, and the unassisted joint torque, are integral to the rule's effectiveness. The assisted torque enables closed-loop optimization that follows the user's internal adaptation. Iterative tuning nurtured cooperative human adaption. The assisted torque provides constraints and stability. ”

Comment 5

5. Introduction of the paper does not set the stage well for the controller. After line 68, the introduction becomes technical (more like methods) and uses terms that are not familiar and confusing when the reader sees them the first time. For example:

Responses:

We thank the reviewer for this valuable feedback. In response, we have revised the manuscript to provide a more comprehensive and methodologically accurate description, shifting from the initial conceptual presentation drafted for a broader audience. Please check below for details.

5.1 Line 69-70, “replacing human effort with exoskeleton assistance is” I could not understand this sentence before reading the whole paper.

Responses:

We have expanded the literature review preceding this statement to include a discussion of feed-forward approaches that imitate joint moments, thereby providing a stronger context.

Original:

“ Wrestling limitations of current personalization-based strategies, we have developed a rapid approach that tried to mimic human natural mechanics while partially replacing human efforts with exoskeleton assistance. ”

Revised (Page 3-4, lines 66-78):

“ In exoskeleton assistance planning, it is intuitive to imitate human biomechanics. Feedforward approaches, which directly map instantaneous joint moment estimates or muscle activities to assistance torque^{8,10,30,44}, embody this straightforward principle. The efficacy of such strategies depends on an efficient and cooperative human-machine interaction. However, their open-loop nature places the burden of achieving this synergy

entirely on the user's neuromuscular system. A user failure at reacting cooperatively and instantaneously may incur system instability and human danger. Recent study⁴⁵ introduced the Interaction Portrait metric to evaluate such interaction properties, underscoring the need for strategies that promote cooperative dynamics. For strategies based on human biomechanics, a proper closed-loop structure can potentially provide necessary environment and constraints to foster a stable and effective exoskeleton-assisting-human interface.

Wrestling limitations of current exoskeleton assistance planning strategies, we have developed a rapid closed-loop optimization approach that tried to mimic human natural mechanics while partially replacing human efforts with exoskeleton assistance. ”

5.2 Lines 70-73. The same issue. English needs improvement.

Responses:

The relevant statements have been clarified through textual revisions and the aforementioned expansion of the literature review on feedback methods, which offers a more complete foundational context.

Original:

“ It stride-wise tuned assistance torque towards a hybrid direction of the real-time human-exoskeleton combined joint torque (referred to as “assisted joint torque” hereinafter) and the pre-measured human joint torque while wearing the exoskeleton without assistance (“unassisted joint torque” or “human torque in zero-torque mode”). ”

Revised (Pages 3-4, lines 78-82):

“ It stride-wise tuned assistance torque towards a hybrid direction of two references: 1) the real-time combined joint torque produced by the human and exoskeleton (referred to as “assisted joint torque” hereinafter), and 2) a pre-measured baseline of the human joint torque recorded while the participant walked wearing the exoskeleton without assistance (“unassisted joint torque” or “human torque in zero-torque mode”). ”

5.3. Line 75: it mentions that the assisted joint torque was made dominant in the learning process while in all the case k_{nom} and k_{dev} are equal. So the exo torque will converge to the weighted average of the unassisted and assisted torques.

Responses:

Thank you for raising this. There was actually a confusion here. Below are the original sentences in question:

“At any time, the desired assistance was set as the weighted average of two items: its prior value at the same time of last stride period; and a tuning guide defined by a weighted sum of the assisted and unassisted joint torques (Fig. 1b, Eq. (1) in Methods). The former was made dominant to ensure a gentle tuning process.”

By “the former”, we meant the former of the two items, i.e., “it prior value”, instead of the assisted joint torque. However, at steady-state, the exoskeleton torque does converge to the weighted sum of the final assisted and unassisted joint torques. We have clarified this in the revised manuscript (Page 4, lines 82-86) as:

“ At any time, the desired assistance was set as the weighted average of two items: its prior value at the same time of last stride period, **which was made dominant to ensure a gentle tuning process**; and a tuning guide defined by a weighted sum of the assisted and unassisted joint torques (Fig. 1b, Eq. (1) in Methods).”

Comment 6

6. Your work is somehow related to feedforward control where desired net torque is estimated and applied by the exoskeleton. However, instead of estimating that, you measure it using force plate and converge to it by an exponential averaging. I see the contribution, but this is not fundamentally different than those works. Discussing this connection would help setting the stage for your contribution in the introduction.

Responses:

This comment is closely related to Comment 4 and we have addressed them together. Please refer to the responses to Comment 4 for details.

Comment 7

7. Terminologies such as normal-shoes walking (-> no exo walking), premature torque (passive exo torque) are confusing.

I could understand line 84-85 only when I read the whole paper. I suggest authors to move this sentence to the method part and try to explain their actual contribution (measuring the net torque and applying a portion of that gradually converged using a exponential averaging method) in a more clear and straight forward way.

Responses:

We have refined terminology, hypotheses and claims throughout the manuscript, including the ones mentioned here, specifically:

- The term 'normal-shoe' mode/walking was originally picked to align with conventions from prior studies in the field. After some debates, we decided to keep this term, rather than changing it to choices like 'no exo walking' or 'normal walking', to stress the fact that shoes were worn and no other interventions were involved. We further clarified the definition at its first appearance in the revised manuscript (Page 5, lines 119-120):

“In validation, optimized assistance profiles were compared with zero-torque and normal-shoe mode in which the participants **walked wearing** their normal shoes without exoskeletons. ”

- The term 'pre-measured' (typo as 'prematured' in the comment) torque was to distinguish with on-line measured human-exoskeleton combined joint torque. We further clarified it in the revised manuscript:

Original:

“ It stride-wise tuned assistance torque towards a hybrid direction of the real-time human-exoskeleton combined joint torque (referred to as “assisted joint torque” hereinafter) and the pre-measured human joint torque while wearing the exoskeleton without assistance (“unassisted joint torque” or “human torque in zero-torque mode”). ”

Revised (Page 3-4, lines 78-82):

“It stride-wise tuned assistance torque towards a hybrid direction of two references: 1) the real-time combined joint torque produced by the human and exoskeleton (referred to as “assisted joint torque” hereinafter), and 2) a pre-measured baseline of the human joint torque recorded while the participant walked wearing the exoskeleton without assistance (“unassisted joint torque” or “human torque in zero-torque mode”).”

- For line 85-85, the original statement about “non-parametric” property of the method, we have kept but clarified it in Introduction to stage the readers with Discussion section, which came before Methods. We have also expanded related discussion in Discussion. Details are below.

In Introduction:

Original in Introduction:

“Non-parametric assistance formulation and direct association between assistance and assisted joint torque saved pre-research time when application scenarios changed.”

Revised in Introduction (Page 4, lines 94-96):

“Non-parametric assistance formulation and direct association between assistance and assisted joint torque saved pre-research time **on human biomechanics to construct and then parameterize assistance profiles** when application scenarios changed.”

Expanded in Discussion 1 (Pages 12-13, lines 334-341):

“Easy deployment of the method to new scenarios arose from the non-parametric formulation, which required no pre-design and parameterization of exoskeleton assistance profiles. By deriving assistance directly from measured joint torques, the algorithm operated independently of ambulation conditions, eliminating the need for explicit gait identification. Transitioning to a new application scenario—whether due to changes in environment or user—simply required re-measuring baseline unassisted torque, identical to initial user calibration. This approach contrasts with traditional human-in-the-loop optimization methods ^{5,17}, which necessitate extensive *a priori* research for specific joints, gait conditions, user populations, and exoskeleton devices.”

Expanded in Discussion 2 (Page 16, lines 427-431):

“Meanwhile, the non-parametric nature of the assistance and the simplicity of the method enable computational demands to scale linearly with number of assisted joints, while optimization time remains unchanged. Thus, the method can be easily extended to multi-joint exoskeleton systems with only neglectable additional computing cost. ”

Comment 8

8. There are some works which is worthy of discussion in the intro:

[1] Durandau, Guillaume, et al. "Neuromechanical model-based adaptive control of bilateral ankle exoskeletons: biological joint torque and electromyogram reduction across walking conditions." IEEE Transactions on Robotics 38.3 (2022): 1380-1394.

[2] Shushtari, M., Foellmer, J. & Arami, A. Human–exoskeleton interaction portrait. J Neuro-Engineering Rehabil 21, 152 (2024). <https://doi.org/10.1186/s12984-024-01447-1>

Responses:

Thank you for bring our attention to these two interesting studies. We have added related discussion in Introduction (Page 3, lines 66-75, revised manuscript) as:

“In exoskeleton assistance planning, it is intuitive to mimic human biomechanics. Feed-forward approaches, which directly map instantaneous joint moment estimates or muscle activities to assistance torque^{8,10,30,44}, embody this straightforward principle. The efficacy of such strategies depends on an efficient and cooperative human-machine interaction. However, their open-loop nature places the burden of achieving this synergy entirely on the user’s neuromuscular system. A user failure at reacting cooperatively and instantaneously may incur system instability and human danger. Recent study⁴⁵ introduced the Interaction Portrait metric to evaluate such interaction properties, underscoring the need for strategies that promote cooperative dynamics. For assistance planing strategies based on human biomechanics, a proper closed-loop structure cam potentially provide necessary environment and constraints to foster a stable and effective exoskeleton-assisting-human interface.”

Comment 9

Note that there was no comment numbered 9, but we kept the original numbering of the comments. No comment 9 was missing or left unaddressed.

Comment 10

10. About the sentence is line 502-504, why increase in net joint torque as a result of increase in exoskeleton joint torque means assistance? what if the user is resisting? A simple example,

Responses:

Thanks for catching this. We understand the confusion here. We have clarified related claims and added analysis for better understanding of ρ .

The original statement of

“Most of the time, ρ is positive and suggests a meaningful assistance in which an increase in exoskeleton assistance leads to a non-decreasing total joint moment and a decrease in human efforts.”

was under the consumption of the previous discussion

“... human feels rather comfortable and safe and will not overreact⁵¹, i.e., $|\rho| \ll 1$.”

In this case, $\rho > 0$, but $|\rho| \ll 1$. Therefore, “increase in net joint torque as a result of increase in exoskeleton joint torque”, as commented, only means human torque is decreasing less than the

increase of exoskeleton input, i.e., exoskeleton torque is not replacing human torque at full efficiency. However, human efforts are still reduced while total joint torque are not dropping. This qualifies as proper assistance.

On the other hand, if a user is resisting, which is not likely to happen with this algorithm due to the comfort and safety experienced by users as discussed above, human efforts are increasing to fight exoskeleton inputs, total joint torque increase will be the combination of exoskeleton input and human torque, and thus greater than the increase of exoskeleton input. In this case, ρ is not only positive, it will be greater than 1. We revised the related paragraphs to clarify these points (Pages 25-27, lines 481-529):

“ Let $\rho(k) = \frac{\partial \tau_{joint}(k)}{\partial \tau_{exo}(k)}$, we have

$$\begin{aligned} \frac{\partial J(k)}{\partial \tau_{exo}(k)} &= \lambda_1(k) \tau_{human}(k) \cdot [\rho(k) - 1] + \lambda_2(k) \tau_{exo}(k) + \lambda_3(k) [\tau_{joint}(k) - \tau_{joint}^{ZT}(k)] \cdot \rho(k) \\ &= [\lambda_2(k) - \lambda_1(k) \rho(k) + \lambda_1(k)] \tau_{exo}(k) + [\lambda_1(k) \rho(k) - \lambda_1(k)] \tau_{joint}(k) \\ &\quad + \lambda_3(k) \rho(k) [\tau_{joint}(k) - \tau_{joint}^{ZT}(k)]. \end{aligned} \tag{5}$$

By gradient descent and the assumption that $\tau_{exo} = \tau_{des}$, with a learning rate of $\lambda(k)$,

$$\begin{aligned} \tau_{exo}(k, i+1) &= \tau_{exo}(k, i) - \lambda(k) \cdot \frac{\partial J(k)}{\partial \tau_{exo}(k)} \\ &= \{1 - \lambda(k) [\lambda_2(k) - \lambda_1(k) \rho(k) + \lambda_1(k)]\} \tau_{exo}(k, i) \\ &\quad + \lambda(k) \lambda_1(k) [1 - \rho(k)] \tau_{joint}(k, i) + \lambda(k) \lambda_3(k) \rho(k) [\tau_{joint}^{ZT}(k) - \tau_{joint}(k, i)]. \end{aligned} \tag{6}$$

Human locomotion is itself optimized and tends to maintain its original biomechanics as much as possible at the presence of external disturbances. Especially under gentle assistance tuning like the approach in this study, in which $\alpha = 0.025$ and $K_{nom} + K_{dev} < 1$, human feels rather comfortable and safe and will not overreact⁵¹, i.e., $|\rho| \ll 1$. Here, negative, zero and positive ρ values respectively indicates that muscle torque reduction is a bit more than, the same as and slightly less than exoskeleton input increase. In any of these cases, total joint torque is not largely affected while human effort is partially replaced by exoskeleton at an efficiency R (Eq. (10)) of about 100%.

$$R = \frac{-\partial \tau_{human}}{\partial \tau_{exo}} \times 100\% = 1 - \rho \tag{7}$$

Any exoskeleton intervention that causes more improvement of mobility than the increase of human efforts is a meaningful assistance. 100% R surely counts. Meanwhile, the tendency to keep natural joint biomechanics, ensured by complex human dynamics, also means a larger coefficient for joint torque changes, λ_3 , relative to λ_1 and λ_2 , in the cost function.

The approach proposed in this study was equivalent to enforcing a small constant positive $\rho(k)$, and thus constant α , K_{nom} and K_{dev} values at index k for an optimization session.

Rewriting Eq. (6), we got the assistance update algorithm in the format of Eq. (1) as below:

$$\begin{aligned}\tau_{exo}(k, i + 1) &= (1 - \alpha)\tau_{exo}(k, i) + \alpha(K_{dev} + K_{nom})\tau_{joint}(k) + \alpha K_{nom} [\tau_{joint}^{ZT}(k) - \tau_{joint}(k, i)] \\ &= (1 - \alpha)\tau_{exo}(k, i) + \alpha [K_{nom}\tau_{joint}^{ZT}(k) + K_{dev}\tau_{joint}(k, i)]\end{aligned}\quad (8)$$

in which

$$\begin{aligned}\alpha &= \lambda(k) [\lambda_2(k) - \lambda_1(k)\rho(k) + \lambda_1(k)], \\ K_{dev} + K_{nom} &= \frac{\lambda_1(k) [1 - \rho(k)]}{\lambda_2(k) - \lambda_1(k)\rho(k) + \lambda_1(k)} \in (0, 1), \\ K_{nom} &= \frac{\lambda_3(k)\rho(k)}{\lambda_2(k) - \lambda_1(k)\rho(k) + \lambda_1(k)} > 0.\end{aligned}\quad (9)$$

Analysis based on the cost function in Eq. (2) aligns with that based on the tuning rule in Eq. (1). Equal weights of nominal and feedback terms in tuning guide, i.e., $K_{nom} = K_{dev}$, together with a small $\rho(k)$, means a big $\lambda_3(k)$, which aligns with previous discussion that small $\rho(k)$ and big $\lambda_3(k)$ come as a pair. For example, $\lambda_3(k) = 9.5\lambda_1(k)$ when $\rho(k) = 0.05$. Meanwhile, smaller K_{nom} and K_{dev} values suggest larger $\lambda_2(k)$, i.e., more intention to keep exoskeleton assistance smaller. This aligned with the results that participants with smaller K_{nom} and K_{dev} had smaller peak optimized torque values (Supplementary Table 2 & Supplementary Figure 11).

*More on ρ , R and human-exoskeleton interaction behavior

Both $\rho = \frac{\partial\tau_{joint}}{\partial\tau_{exo}}$ and $R = -\frac{\partial\tau_{human}}{\partial\tau_{exo}}$ describe human body's reactions to exoskeleton input. They are governed by the internal physical and chemical dynamics of human body. The definition of ρ was introduced to design, by inverse dynamics, an exoskeleton torque tuning rule (Eq. (1)) that governs how the exoskeleton reacts to human actions, i.e., $\frac{\partial\tau_{exo}}{\partial\tau_{joint}}$ or $\frac{\partial\tau_{exo}}{\partial\tau_{human}}$. Therefore, the values of ρ solely without the knowledge of $\frac{\partial\tau_{exo}}{\partial\tau_{joint}}$, sometimes cannot fully portray the human-exoskeleton interaction behaviors.

When $|\rho| \ll 1$ as produced by the proposed method in this study, human effort is replaced by exoskeleton at an efficiency of $R \approx 100\%$. This qualifies as effective exoskeleton assistance while maintaining original mobility. In this region, $-1 \ll \rho < 0$, $\rho = 0$ and $0 < \rho \ll 1$ correspond to slight reduction, maintenance, and slight augmentation of the total joint torque, respectively.

Beyond the $|\rho| \ll 1$ region and discussion of this rapid heuristic optimization method, if $0 < \rho \leq 1$ ($0 \leq R < 100\%$), increase in exoskeleton torque causes decrease or no change in human torque. Total joint torque is thus augmented.

If $\rho > 1$, increase in exoskeleton torque will lead to increase in human torque, which means the user is resisting exoskeleton intervention. Although joint torque is further enlarged, this

situation may incur instability and endanger the user, depending on the exoskeleton high level controller for input torque planning, i.e., $\frac{\partial \tau_{exo}}{\partial \tau_{joint}}$.

If $\rho < 0$ (i.e., $R > 100\%$), the user feels insecure and attempts to disengage or ‘escape’ from the exoskeleton. Human torque decreases more than exoskeleton torque increases, leading to a net reduction in total joint torque.

However, this analysis is about instant changes in total joint torque. To fully assess joint mobility and human-exoskeleton interaction modes, changes in joint torque and joint motion must be considered together over the entire gait cycle. ”

Comment 11

11. Line 506: what does efficiently mean here?

Responses:

By “efficiency” (typo as ‘efficiently’ in the comment) we meant that the rate at which human torque were replaced by exoskeleton torque, i.e., $\frac{-\partial \tau_{human}}{\partial \tau_{exo}}$, which equals to $\frac{-\partial(\tau_{joint} - \tau_{exo})}{\partial \tau_{exo}} = 1 - \frac{\partial \tau_{joint}}{\partial \tau_{exo}} = 1 - \rho$. We have clarified this in the revised manuscript:

Original:

“Human mobility is thus maintained or improved while human effort is partially replaced by exoskeleton at an efficiency (i.e., $1-\rho$) close to 1. ”

Revised (Page 25, lines 483-492):

“Human locomotion is itself optimized and tends to maintain its original biomechanics as much as possible at the presence of external disturbances. Especially under gentle assistance tuning like the approach in this study, in which $\alpha = 0.025$ and $K_{nom} + K_{dev} < 1$, human feels rather comfortable and safe and will not overreact⁵¹, i.e., $|\rho| \ll 1$ (Supplementary Figure 14). Here, negative, zero and positive ρ values respectively indicate that muscle torque reduction is a bit more than, the same as and slightly less than exoskeleton input increase. In any of these cases, total joint torque is not largely affected while human effort is partially replaced by exoskeleton at an efficiency R (Eq. (10)) of about 100%.

$$R = \frac{-\partial \tau_{human}}{\partial \tau_{exo}} \times 100\% = 1 - \rho \quad (10)$$

Any exoskeleton intervention that causes more improvement of mobility than the increase of human efforts constitutes meaningful assistance. 100% R clearly represents one such instance. ”

Additional analysis on ρ and R are added (Pages 26-27, lines 506-529; previously fully quoted in responses to Comment 10, page 48 of this file) as:

“

***More on ρ , R and human-exoskeleton interaction behavior**

Both $\rho = \frac{\partial \tau_{joint}}{\partial \tau_{exo}}$ and $R = -\frac{\partial \tau_{human}}{\partial \tau_{exo}}$ describe human body’s reactions to exoskeleton input

.....

.....

..... However, this analysis is about instant changes in total joint torque. To fully assess joint mobility and human-exoskeleton interaction modes, changes in joint torque and joint motion must be considered together over the entire gait cycle. ”

Comment 12

12. Line 540: “The value of $K_{dev} = K_{nom}$ for the optimization was set based on the amount of assistance the participant was willing to tolerate ([0.175, 0.25]).” K_{dev} and k_{nom} is more than 0.3 according to Supplementary Table 2. The range seems to be wrong. Please clarify.

Reseponses:

3 related gain values were listed in Supplementary Table 2, namely K_{nom} , K_{dev} and $K_{nom} + K_{dev}$. The third one ($K_{nom} + K_{dev}$) was the summation of the first two. Since $K_{dev} = K_{nom}$ in this study, it actually was twice the values of K_{nom} or K_{dev} . We think it might be confused with K_{nom} or K_{dev} . The original purpose of listing this value in the table was to show its similarity with the last item, i.e., τ_{peak} (% of peak unassisted torque). We have clarified in the revised manuscript (Page S16, Supplementary Table 2) by changing the header row of the table from

Participant	K_{nom}	K_{dev}	$K_{nom} + K_{dev}$	τ_{peak} (Nm kg ⁻¹)	τ_{peak} (% of peak unassisted torque)
P1	0.25	0.25	0.5	0.712	52.1
⋮	⋮	⋮	⋮	⋮	⋮
P10	0.175	0.175	0.35	0.493	35.2

to

Participant	K_{nom}	K_{dev}	$K_{nom} + K_{dev}$ ($2K_{nom}$, or $2K_{dev}$)	τ_{peak} (Nm kg ⁻¹)	τ_{peak} (% of peak unassisted torque)
P1	0.25	0.25	0.5	0.712	52.1
⋮	⋮	⋮	⋮	⋮	⋮
P10	0.175	0.175	0.35	0.493	35.2

Comment 13

13. Line 551: referring “NW-ZT-Gen-Opt-Opt-Gen-ZT-NW” , these are not defined previously as I can see.

Responses:

We have clarified in the revised manuscript (Page 28, lines 560-562):

Original

“ All conditions were tested in a double-reversal order (NW-ZT-Gen-Opt-Opt-Gen-ZT-NW). ”

Revised:

“ All conditions were tested in a double-reversal order of NW (normal-shoe walking)–ZT (zero-torque mode)–Gen (generic assistance mode)–Opt (optimized assistance mode)–Opt–Gen–ZT–NW. ”

Comment 14

14. How k (time index) is estimated? Is it based on time? If so, how sensitive this approach is to variations (transitions) in gait timing? Did you use a gait phase estimator?

Responses:

Thank you for this interesting point. In the current implementation of the method as tested in this manuscript, k was indeed based on absolute time, representing the number of control cycles (2 ms) elapsed in the current cycle since the last detected heel strike. We acknowledge that this approach relies on temporal measurement rather than explicit gait phase estimation.

Despite this design choice, the method demonstrated robust performance across both laboratory settings (with controlled walking speeds) and outdoor tests (with self-paced walking) in the presence

of natural gait timing variations. As shown in Fig. R1, the stride times for all participants showed natural variability, yet our optimization algorithm performed effectively throughout. This effectiveness can be attributed to the algorithm’s stride-wise iterative tuning mechanism. It adjusted assistance torque gradually and comfortably, and thus provided fair robustness against gait time.



Fig. R1: Gait time of all strides during optimization for all 10 participants in main experimental study.

We recognize that implementations incorporating gait phase estimators—using relative time or kinetic information such as joint angles—could further enhance performance in scenarios with more rapid or substantial gait variations. Furthermore, our group recently developed a strategy(Yin et al., TNSRE, 2025) to generalize an absolute-time-based assistance profile, achieved through optimization under a fixed gait condition, to different walking speeds and individual strides. It can be be directly applied to future iterations of this framework. These choices represent promising directions for future refinement.

Ultimately, the primary contribution of this work lies in establishing a framework for rapid closed-loop optimization characterized by: (a) an instantaneously measurable interaction-related feedback signal, (b) a physiologically reasonable tuning direction, and (c) a direct continuous association between feedback and the optimized variable. While the current implementation utilizes absolute time indexing, the underlying philosophy is compatible with various signal types and update mechanisms.

We have expanded the discussion of these potential implementations in the Conclusion and Future Work section (Pages 16-17, lines 433–453) to emphasize that the choice of feedback signals, guidance mechanisms, and update rules can be adapted beyond the specific approach presented here. We believe this flexibility further strengthens the generalizability and potential impact of the proposed framework.

Thank you again for this insightful comment, which has helped us clarify both the robustness of the current implementation and the exciting possibilities for future development.

Related discussion in Conclusions and future work section:

“The keys to the success of the proposed method, as discussed, included a) an instantaneously measurable interaction-related feedback, b) a reasonable tuning direction, and c) a continuous direct association between the feedback and the variable to be optimized. We do not claim the necessity to choose assisted joint torque as feedback, or unassisted joint torque

as nominal guide, or assistance torque as variable, or updation rule based on absolute time in stride. Neither do we claim the necessity of matching data types between feedback and variable. Other interaction-related low-noise signals, such as interface impedance, power or energy, of the coupled system or a subsystem, might work as feedbacks. Sources other than experimental evaluations, such as simulations and prior studies, might be used to generate guides. Other forms of intervention to human, such as admittance, impedance, or motion profiles, might work as variables. **Updation of variables from prior values might be based on relative time in stride, kinetic information such as joint angles, or other kinds of gait phase estimators.** Data-driven neural-network-based techniques might also be incorporated to enhance various parts of the process, e.g., joint torque estimation as in^{22,30}. These and more possibilities are yet to be explored and verified. Further studies of the current implementation are also beneficial. For example, the best learning rates and optimization durations might differ for various applications²⁶. Different relative weights between the nominal and the feedback terms in the guide might cause different behaviors and performances. **Effects of torque estimation errors are not yet rigorously investigated.** Insights of human-robot interaction and coupling mechanisms possibly revealed by the explicit model deserve deeper investigations. **Moreover, the assistance profiles achieved through optimization under fairly fixed conditions can be generalized to practical scenarios with varying speeds and individual strides⁵³.**

References in Responses

[Zhang et al., 2017]: Juanjuan Zhang, Pieter Fiers, Kirby A Witte, Rachel W Jackson, Katherine L Poggensee, Christopher G Atkeson, and Steven H Collins. Human-in-the-loop optimization of exoskeleton assistance during walking. *Science*, 356(6344):1280–1284, 2017

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Response to the Reviewers

Manuscript #: COMMS-25-0240-A:

Interaction-based rapid heuristic optimization of exoskeleton assistance during walking

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NOTE that:

- ◇ All reviewer comments are in **Sans Serif** font in **BLACK**.
- ◇ All author responses are in **Sans Serif** font in **BLUE**.
- ◇ All quotes of manuscript content are in **Roman** font, mostly in **BLACK**.
- ◇ All changes are highlighted in **MAROON** in the revised manuscript, including those quoted in this file.

ACKNOWLEDGEMENT

We sincerely thank the reviewers for their thorough review and highly insightful comments, which have significantly improved the final manuscript. We have addressed all feedback, and our detailed responses follow.

Reviewer 1

Overall Comments:

Thank for you thoroughly addressing each of my comments. The corresponding updates to the manuscript, especially the additional experiments, help clarify how the proposed approach compares to prior literature; however, I have a few remaining comments.

Responses:

We thank the reviewer again for the thorough review and constructive suggestions. We have made revisions accordingly to improve the clarity and accuracy of our presentation, including:

1. Clarified metabolic benefit compared to Slade et. al., 2022.
2. Clarified description of results and softened all claims related to comparisons with both proportional joint moment strategies.

Please check the point-by-point responses below.

Comments Group 1:

1. When mentioning that the metabolic cost reductions in this study were similar to those of Slade et al., please make it clear that Slade's metabolic reductions were about twice as large but used bilateral assistance compared to the unilateral assistance in this study.

Responses:

We thank the reviewer for this valuable feedback and helpful suggestion. We have added statements in the revised manuscript (Page 12, lines 316-220) to clarify this:

“The proposed method achieved comparable ($n = 10$, 20.4% vs $n = 11$, 24.2%⁵; No statistically significant difference) energy consumption reduction to state-of-the-art metabolism-driven CMA-ES optimizations^{5,17}. (The apparent higher metabolic reduction in ¹⁷ was based on a bilateral ankle exoskeleton system. However, ¹⁷ exhibited metabolic reduction capabilities equivalent to ⁵. It was an efficient implementation of ⁵ for metabolism minimization with the same optimization algorithm (CMA-ES) but a faster metabolism estimation method. The same experimental study in ¹⁷ also verified this.) Notably, this result was attained while optimizing for reduction in joint torque, a local mechanical correlate to muscle activity, rather than whole-body energy cost. This suggests that maintaining user comfort throughout the optimization process may inherently support metabolic efficiency. Furthermore, our approach

achieved state-of-the-art reductions in both metabolic cost and muscle activity with a single, two-minute optimization process, whereas prior approaches required separate protocols to minimize each metric individually^{5,17}. ”

Comments Group 2:

2. I greatly appreciate the addition of the proportional joint torque experiments, which greatly help compare this approach to prior work; however, I have a few concerns about the methods and interpretation of these results.

Responses:

We thank the reviewer for the insightful comments on the presentation of our comparison with the proportional joint moment strategies. We have refined the descriptions and moderated the claims as detailed below.

- a. In “Comparison to assistance proportional to unassisted joint torque,” I would have expected the authors’ approach be compared to the method that applies a portion of the real-time torque (more representative of the state-of-the-art in proportional joint torque control) opposed to a portion of the open-loop baseline from zero-torque. Please justify why this was used instead.

Responses:

We thank the reviewer for this valuable question. To provide a comprehensive validation, we have included experimental comparisons with **both** strategies:

- Assistance proportional to the **unassisted joint torque** (the open-loop baseline from zero-torque), presented in the subsection “Comparison to assistance proportional to unassisted joint torque” in Results.
- Assistance proportional to the **real-time assisted joint torque**, presented in the subsection “Exoskeleton assistance proportional to real-time assisted joint torque. We have revised this title to “**Comparison to assistance proportional to real-time assisted joint torque**” (Page 8, line 193) for greater clarity.

The primary purpose to include both was to better portray the necessity and contributions of various elements of the proposed tuning law:

$$\tau_{exo}(k, i + 1) = (1 - \alpha)\tau_{exo}(k, i) + \alpha[(K_{dev} \cdot \tau_{joint}(k, i) + K_{nom} \cdot \tau_{joint}^{ZT}(k, i)].$$

The apparent features of this rule include an iterative tuning process and the steady-state convergence of exoskeleton torque to $[K_{dev} \cdot \tau_{joint}(k) + K_{nom} \cdot \tau_{joint}^{ZT}(k)]$. These properties motivated multiple questions from the reviewers, which we synthesized as:

- (1) What is the relative importance of the iterative tuning process versus the baseline reference τ_{joint}^{ZT} ?
- (2) How does the full method performance compare to a strategy using *only* the baseline torque: $\tau_{exo} = (K_{dev} + K_{nom}) \cdot \tau_{joint}^{ZT}$?
- (3) How does it compare to a state-of-the-art strategy using *only* real-time torque: $\tau_{exo} = (K_{dev} + K_{nom}) \cdot \tau_{joint}$?
- (4) What are the functional roles of (a) the iterative process, (b) real-time assisted joint torque τ_{joint} , and (c) unassisted joint torque during zero-torque walking τ_{joint}^{ZT} ?

In brief, all three components (a)-(c) are integral to the method's effectiveness. The assisted joint torque (τ_{joint}) provides real-time feedback, enabling closed-loop optimization that follows the user's internal adaptive process. The iterative tuning ensures instantaneous, cooperative and gradual human adaption to intervention. The unassisted joint torque (τ_{joint}^{ZT}) provides a stabilizing baseline, constraining the assistance to a physiologically plausible range.

The two new experimental sub-studies provided direct answers to questions (2) and (3), offered additional support data for (1) and (4), and strengthened the overall argument of the manuscript.

- b. "However, their open-loop nature places the burden of achieving this synergy entirely on the user's neuromuscular system. A user failure at reacting cooperatively and instantaneously may incur system instability and human danger." I would not consider the referenced controllers that actively estimate real-time joint torque "open loop" since they immediately react to changes in the user's motion. Please clarify that the more recent approaches to proportional joint torque control have removed the open loop nature of previous controllers by using real-time joint torque estimates.

Responses:

We thank the reviewer for this excellent suggestion. We have revised the description of proportional real-time joint moment from being "feedforward" and "open loop" to the more accurate "positive feedback loop." throughout the revised manuscript.

For example, the sentence mentioned was changed from:

"However, their open-loop nature places the burden of achieving this synergy entirely on the user's neuromuscular system."

to (Page 3, line 68-69):

"However, their **intrinsic positive-feedback-loop** nature places the burden of achieving this synergy entirely on the user's neuromuscular system."

Another example:

"However, our method implements a closed-loop optimization, whereas feedforward paradigms operate in an open-loop manner."

was changed to (Page 14, line 368-370):

“However, our method implements a closed-loop optimization **constrained around the baseline unassisted joint moment**, whereas **proportional-real-time-moment paradigms can be characterized as operating in a positive-feedback-loop manner.** ”

- c. “Should a user respond defensively or adapt poorly, the system may enter vicious cycles with drifting and dangerous assistance. This was supported by the lack of statistical significance in muscle benefit compared to zero-torque condition (Supplementary Figure 12).” Supplementary Figure 12 shows the alternative approach was quite effective (35% reduction in muscle activation, which is very similar to the proposed approach). Lack of statistical significance is more likely due to sample size here. Please update.

Responses:

Thank you for this insightful observation. We agree that attributing the finding solely to a lack of statistical significance is an oversimplification. The more complete explanation involves both user experience and the constraints on our experimental comparison.

As noted in the manuscript, all participants described the proportional real-time joint moment as 'difficult to control', whereas the heuristic optimization was consistently rated as 'rather comfortable'. Furthermore, the data in Supplementary Figure 12 comes from only 4 out of 6 recruited participants who could tolerate the high gain (0.5) required for that protocol.

Therefore, a more equitable comparison of muscular benefits is between these participants and those from the main heuristic study who achieved a similar maximum effective gain of 0.5 (P1, P2, P3, P7 in main study, and P2, P7, P12 in proportional-real-time-moment study). In this matched comparison, the soleus activity reduction with our method was 43.6 ± 12.7 %, substantially greater than the 35.8 ± 9.3 % achieved with the proportional real-time moment. We have updated the manuscript to reflect this more accurate and fair analysis:

(Page 14, lines 374-380)

“Should a user respond defensively or adapt poorly, the system may enter vicious cycles with drifting and dangerous assistance. **This interpretation was consistent with participant feedback describing the strategy as “difficult to control” and the observed lower muscle benefit compared to our method ($35 \pm 9.3\%$ reduction from zero-torque condition for 0.5 gain, Supplementary Figure 12, vs. $43.6 \pm 12.7\%$ in our method for participants with $K_{nom} + K_{dev} = 0.5$, Supplementary Figure 5; the lack of statistical significance was likely due to small sample size).** ”

- d. The exoskeleton torque of Gen2 in Supplementary Figure 13 seems very similar to the optimized torque. If possible, please provide more details of why Gen2 torque was intolerable.

Responses:

Thank you for this insightful question. We would like to clarify them separately as follows:

(1) Similarity of Torque Profiles:

During the additional experiments for the Gen2 comparison, we encountered measurement instability from the treadmill system. This technical issue prevented us from safely testing higher torque levels, as was done in the main study. Consequently, the experiment was conducted at lower torque levels, where the inherent differences between the assistance profiles and their physiological benefits are naturally less pronounced, leading to the observed similarity in the torque traces and small differences in muscular benefit.

(2) Intolerance of the Gen2 Profile:

Despite the seemingly similar torque profiles, participants reported the Gen2 condition as uncomfortable for a fundamental reason related to human-exoskeleton interaction, which will be amplified for both higher torque and less smooth assistance due to noisy as happened in this experiment:

- The unassisted joint torque represents a stable equilibrium for the user adapting to the exoskeleton's passive structure.
- Imperfections in the human-machine interface mean exoskeleton actuation cannot perfectly replace muscle actuation. As a result, the joint torque under assistance inevitably shifts to a new equilibrium.
- Our proposed iterative tuning efficiently guides the user-exoskeleton system toward a new, globally optimal equilibrium. In contrast, the Gen2 strategy applies a fixed portion of the unassisted torque, which fails to account for this necessary equilibrium shift. It essentially forces the user to compensate for a control law that is misaligned with the new dynamic state.

Therefore, the reported intolerance to Gen2 is attributed to the suboptimal and rigid nature of its assistance profile, which creates a conflicting interaction rather than a cooperative one. Of course, this phenomenon will be amplified for both higher torque and less smooth assistance due to noisy as happened in this experiment.

- e. "Formulating exoskeleton assistance by the proposed iterative tuning outperformed directly asserting a fixed portion of unassisted joint torque (Supplementary Figure 13)." This result was not statistically significant and the difference of 5% between the Gen2 and Optimized conditions is fairly small relative to other comparisons in this study. Please soften this statement accordingly.

Responses:

We thank the reviewer for this suggestion. As noted in our response to point [d.], the observed differences between strategies were attenuated at the lower torque levels tested in this specific experiment.

We have tune down related claim to (Page 14, lines 387-389):

“Formulating assistance via the proposed iterative tuning appeared to lead to improved outcomes compared to directly applying a fixed portion of unassisted joint torque (Supplementary Figure 13).”

- f. Given the comments above, the remainder of the discussion comparing the proposed approach to proportional joint torque control should also be softened.

Responses:

Thank you for these wonderful and thorough comments. We have accordingly softened the entire discussion over comparison with proportional-moment strategies (Page 14-15, lines 364-399):

“The proposed iterative tuning method appeared to offer enhanced comfort, stability and effectiveness compared to approaches that formulates assistance directly from real-time joint moments or muscle activities^{8,10,30,44}. Both strategies posit positive correlations between exoskeleton torque and human biomechanics, and thus may have performance dependent on the inner dynamics of how human body reacts to intervention. However, our method implements a closed-loop optimization constrained around the baseline unassisted joint moment, whereas proportional-real-time-moment paradigms can be characterized as operating in a positive-feedback-loop manner. The proposed method (Eq. (1)) asserts minimal changes per stride and was designed to provide sufficient reaction time for human adaptation, which is hypothesized to promote comfort and cooperative responses. In contrast, proportional-moment approaches risk introducing abrupt intervention changes. Their efficacy therefore hinges on the user’s ability to adapt cooperatively and instantaneously. Should a user respond defensively or adapt poorly, the system may enter vicious cycles with drifting and dangerous assistance. This interpretation was consistent with participant feedback describing the strategy as “difficult to control” and the observed lower muscle benefit compared to our method ($35 \pm 9.3\%$ reduction from zero-torque condition for 0.5 gain, Supplementary Figure 12, vs. $43.6 \pm 12.7\%$ in our method for participants with $K_{nom} + K_{dev} = 0.5$, Supplementary Figure 5; the lack of statistical significance was likely due to small sample size). The inter-personal variability, coupled with observed user intolerance, suggested that the proportional joint torque strategy may be inherently unstable and sensitive to individual user dynamics and adaptation. Besides gradual adjustments, presence of the nominal unassisted torque in the tuning rule was intended to prevent undesirable human reactions from destabilizing the system. Therefore, the heuristic optimization is suggested to be more robust and effective, particularly for users with gait impairments, ensuring both comfort and stability throughout adaptation.

Formulating assistance via the proposed iterative tuning appeared to lead to improved outcomes compared to directly applying a fixed portion of unassisted joint torque (Supplementary Figure 13). The unassisted joint torque represents an equilibrium point resulting from the human user’s adaptation to the exoskeleton’s mechanical structure. Due to imperfect human-machine interface, exoskeleton actuation cannot fully replace muscle actuation. Therefore, assisted joint torque **is expected to** inevitably deviate from the unassisted baseline as the system shifts to a new equilibrium under shared human–exoskeleton actuation (Fig. 4A). Different assistance profiles necessarily alter this equilibrium state. Within the resulting state space, one or several optimal equilibria **may** exist. The iterative tuning **is designed to provide** provided an efficient pathway to converge to such optima. In contrast, applying a fixed portion of the unassisted torque **may fail to** account for equilibrium shifts due to altered actuation modes and is therefore **theorized to be** inherently suboptimal. This **provides a potential explanation** why participants found the Gen2 condition uncomfortable, despite the low assistance torque and thus minimal difference in muscle benefit with optimized condition. ”

Reviewer 5

Comments:

I appreciate authors for their thorough revisions. I'm satisfied with the current manuscript, but I'd like to address my comment about the variable λ . I believe the authors interpreted my comment to mean they must include the variable k in their equations. However, I think it's better to remove k for improved readability. My comment was more about having a cost function with a set of variable coefficients. If you agree that λ' is variable, then your cost function is also variable, meaning it changes slightly at each optimization step. This isn't intuitive because, during optimization, the cost function structure is typically kept constant, not variable with respect to the step.

Responses:

Thank you for this insightful comment, which highlights an important aspect of our methodology that warrants clarification. We appreciate the opportunity to clarify this point.

The parameter k in our analysis represents the index within a single gait cycle, not the count of elapsed cycles. Consequently, the iterative tuning rule operates by updating the exoskeleton assistance profile independently at each discrete point k in the gait cycle. This framework implies a parallel set of gradient-descent optimization processes—one for each k —each characterized by its own fixed coefficients $\lambda_1(k)$, $\lambda_2(k)$, $\lambda_3(k)$.

All of these independent processes are updated once per stride. It is important to note that the cost function for a specific index k remains constant across strides; however, the function itself is unique for each value of k .

We have clarified in the revised manuscript:

From:

“ This tuning algorithm realized a gradient descent optimization process that minimizes the combined cost of human biological joint moment, exoskeleton assistance and the deviation of total assisted joint torque from the unassisted human joint torque.

Consider a stride-wise cost function $J_{stride} = \sum_{k=1}^{StrideEnd} J(k)$, in which $J(k)$ stands for the cost function for index k within a gait cycle, formulated as

$$J(k) = \frac{1}{2}\lambda_1(k)\tau_{human}^2(k) + \frac{1}{2}\lambda_2(k)\tau_{exo}^2(k) + \frac{1}{2}\lambda_3(k)[\tau_{joint}(k) - \tau_{joint}^{ZT}(k)]^2. \quad (1)$$

τ_{human} is the human biological joint moment, τ_{exo} is the exoskeleton assistance torque, τ_{joint} is the human-exoskeleton combined joint moment, τ_{joint}^{ZT} is the unassisted human joint torque, and $\lambda_1(k)$, $\lambda_2(k)$, $\lambda_3(k)$ are non-negative constants for index k . ”

to (Page 24, lines 481-489):

“ This tuning algorithm realized a gradient descent optimization process, **composed of a series of independent sub-processes**, that minimizes the combined cost of human biological joint moment, exoskeleton assistance and the deviation of total assisted joint torque from the unassisted human joint torque.

Consider a stride-wise cost function $J_{stride} = \sum_{k=1}^{StrideEnd} J(k)$, in which $J(k)$ stands for the cost function for index k within the gait cycle, formulated as

$$J(k) = \frac{1}{2}\lambda_1(k)\tau_{human}^2(k) + \frac{1}{2}\lambda_2(k)\tau_{exo}^2(k) + \frac{1}{2}\lambda_3(k)[\tau_{joint}(k) - \tau_{joint}^{ZT}(k)]^2. \quad (2)$$

τ_{human} is the human biological joint moment, τ_{exo} is the exoskeleton assistance torque, τ_{joint} is the human-exoskeleton combined joint moment, τ_{joint}^{ZT} is the unassisted human joint torque. **The coefficients $\lambda_1(k)$, $\lambda_2(k)$, $\lambda_3(k)$ are non-negative and remain fixed for each specific index k .**”