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# Perception of Powered Ankle Exoskeleton Actuation Timing During Walking: A Pilot Study

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*Abstract*— **Actuation timing is an important parameter in powered ankle exoskeleton control that can significantly influence user experience and human-system performance. Previous studies have investigated the actuation timing through optimization under different objective functions, such as minimizing metabolic cost. However, little is known about people's psychological sense of actuation timing. This pilot study measured two subjects' sensitivity to small changes in actuation timing during walking. The just-noticeable difference (JND) threshold was determined via a fitted psychometric function, which quantified subjects' performance in discriminating between a pair of actuation timings. Subjects could detect changes of 3.6% and 6.8% stride period in actuation timing respectively, showing the difference in perception between individuals. The results from this pilot study provide a preliminary understanding of human perception towards exoskeleton control parameters, which offers insight on individual differences in exoskeleton usage and informs exoskeleton precision requirements to minimize undesired human-system interaction.**

## I. INTRODUCTION

Exoskeletons are wearable technologies that aim to assist activities of daily living and the most common goal of an exoskeleton is to extend human speed, strength, and endurance [1]. Active and passive exoskeletons are both being widely explored. While passive exoskeletons are typically cheaper and lighter, active devices are able to provide a diverse set of torque profiles [2]. Actuation timing is one of the critical properties that affects user experience and human-system performance in active exoskeleton applications. Several studies support that there exists the optimal actuation timing that can significantly reduce the metabolic cost [3]–[5]. Ingraham *et al.* [6] showed the existence of preferred actuation timings by exoskeleton users. The walking mechanics and muscle activation can also be affected by different control parameter selections [7]. However, the underlying perception of relevant exoskeleton control parameters is unknown, and can influence the optimal or preferred solution. An important consideration in exoskeleton control architectures is to minimize the perceived interaction forces between human and exoskeleton [8]. Therefore, quantifying people's ability to perceive the changes in exoskeleton actuation timing can provide insights into the device resolution requirements, and can also improve the implementation of optimization algorithms in how the solution space is investigated.

Psychophysical experiments are typically used to assess human sensitivity to changes in stimuli. Forced-choice tasks, especially two-alternative forced choice (2AFC) task [9] are widely used for its ability to eliminate biased responses from subjects, and are reliable in assessing human intrinsic proprioception and human perception of wearable technologies [10]–[12]. However, forced-choice procedures sometimes can be infeasible when subjects cannot detect relative magnitudes, but can only know if the two choices are the same or not. In this study, for instance, first-time exoskeleton users can have difficulty specifying relative timing even when they could perceive a difference. This difficulty may arise from inexperience with the exoskeleton and assessing the relative timing of their natural step with respect to the external torque provided, which is generally not a requirement even for experienced users. Therefore, a yes-no task was implemented in this study. Green [13] introduced a modified logistic function as the basic psychometric function, which incorporated the estimate of the false-alarm rate, and has been applied previously in acoustic perception [14].

In this pilot study, we measured two subjects' ability to differentiate actuation timings of an ankle exoskeleton that support gait. To quantify subjects' sensitivity, a 50% different response was used as the just-noticeable difference (JND) threshold, with correction if subjects' response bias was detected, as in Green [13]. Knowing people's perception threshold helps with design requirements for the precision of exoskeleton timing to minimize undesired interaction between the user and the robot. We can set precision parameters to meet the lower threshold, which corresponds to users with greater perception of changes. By designing for these users, we also accommodate users across the perceptual spectrum.

## II. METHOD

### A. Subjects

Two male subjects (Table I) were recruited to participate in the study. Subjects were both healthy, able-bodied with no leg or foot injuries, and had no prior experience with any lower-body exoskeleton. Both of them wore US Men's 10 shoes. Subjects provided written informed consent, which was approved by the University of Michigan Institutional Review Board.

### B. Exoskeleton

Subjects wore ExoBoots [Dephy, Inc., Maynard, MA], a powered ankle exoskeleton for walking augmentation [15]. The ExoBoot assists people walking by providing positive

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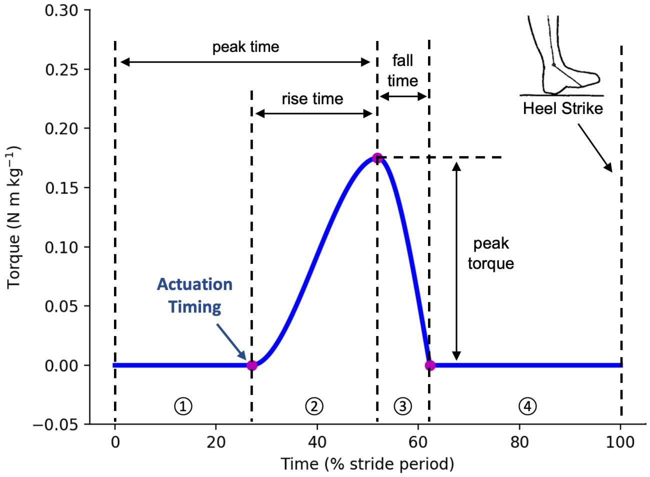



Fig. 1: The torque profile was provided by the exoskeleton to assist walking. Time was normalized to stride period, and was divided into four regions. No torque was applied in region 1 and 4. During region 2 and 3 where torque was produced, the pattern was applied as a cubic spline defined by four parameters: peak torque, peak time, rise time, and fall time. The heel strike was defined as 0% stride period.

mechanical power to the ankle during push-off. We used the torque profile introduced by Zhang *et al.* [16] for its simplicity and effectiveness. The original torque profile was determined by four parameters: peak torque, peak time, rise time, and fall time (Fig. 1). In this study, the rise time and the fall time were set to be 25.3% and 10.3% stride period, respectively. The peak torque was set to be 0.175 Nm/kg due to the mechanical constraint of the ExoBoots. These three parameters were constant throughout the whole experiment, and the peak time was the only variable. To be more consistent with other literature [4], [5], we used actuation timing instead of peak time in this paper. The actuation timing, which was the timing of exoskeleton actuation onset (Fig. 1), was calculated as:

$$\text{Actuation Timing} = \text{Peak Time} - \text{Rise Time} \quad (1)$$

Time was normalized to stride period. A stride period started from the heel strike of one foot and ended at the heel strike of the same foot. We detected the heel strike using ankle angular velocity measured from the ExoBoots on-board gyroscope. Current stride period was calculated as the average of the previous three stride periods.

An Android application was developed to change the actuation timing and record subjects' response. During the preferred timing selection, 'Increase Time' and 'Decrease Time' buttons were used to increase and decrease the actuation timing of exoskeleton by 1% stride period, respectively. In the actuation timing perception test, 'Different' and 'Equal' buttons recorded subjects' response following the protocol described in Section II.C. The Android application communicated with the ExoBoots through a Raspberry Pi (Model: 4B, Cambridge, UK). The data sampling rate of the ExoBoots was set to 1000 Hz.

TABLE I: Two Subjects' Information

| | Age (years) | Height (m) | Mass (kg) | Self-Selected Speed (m/s) | Preferred Timing (% stride period) |
|---|---|---|---|---|---|
| Subject 1 | 28 | 1.65 | 63.7 | 1.10 | 25% |
| Subject 2 | 23 | 1.82 | 57.8 | 1.35 | 27% |

### C. Protocol

The whole study consisted of two parts. Subjects first selected their preferred actuation timing using the Android application while walking on the treadmill. Then their sensitivity to the change in actuation timing was quantified by their ability to tell if the comparison timing and the reference timing were equal or different in each trial.

*1) Preferred Timing Selection:* Subjects walked on the treadmill at their self-selected speed (Table I) with the exoskeleton powered-on for 5 minutes to get familiar with the ExoBoots. The initial actuation timing for this familiarization period was 26% stride period. Then they were asked to select an actuation timing in which they felt most comfortable walking with the ExoBoots. They were free to press the 'Increase Time' and the 'Decrease Time' buttons on the application to change the actuation timing. Subjects were asked to take a minimum of 5 strides per timing, and were encouraged to explore as many different timings as they could until the timings were too early or too late to walk comfortably.

*2) Actuation Timing Perception:* Actuation timing perception was measured after preferred timing selection with a short break in between. Subjects walked on the treadmill at the self-selected speed with the ExoBoots. Each trial presented a pair of timings, a reference timing and a comparison timing. The order of the reference and comparison timings in each trial is random. Each timing lasted for 5 strides and subjects were notified when each timing started. Subjects

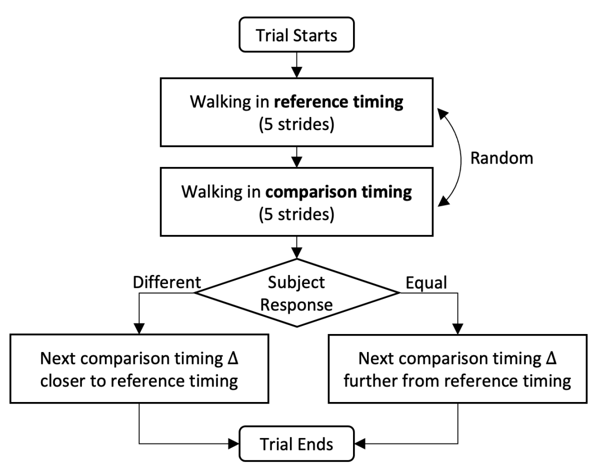
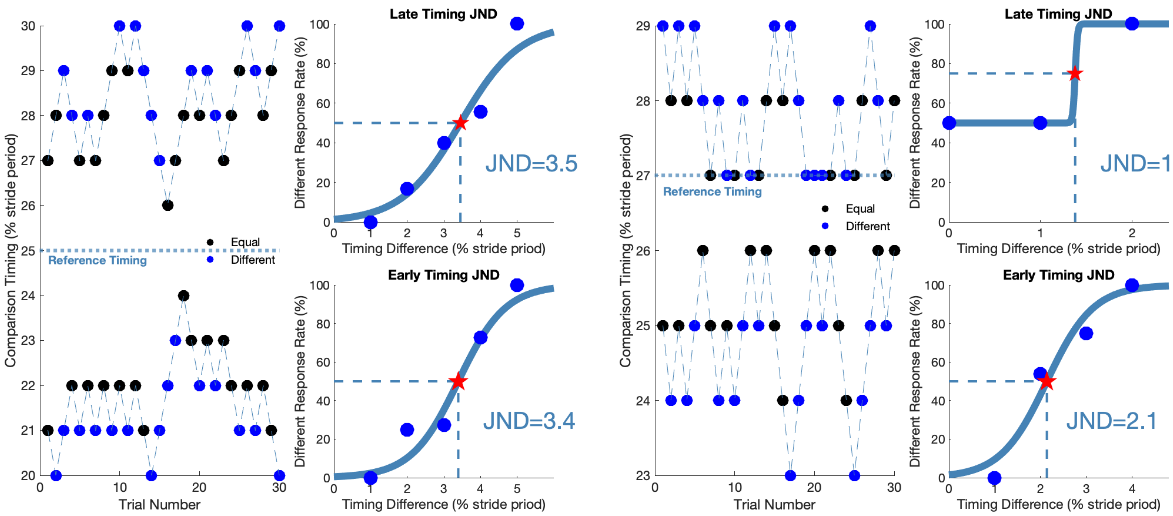



Fig. 2: The protocol of a single trial. The reference timing and the comparison timing were in sequence but in random order. The simple up-down method was used to determine the next comparison timing value.




(a) Subject 1 (b) Subject 2

Fig. 3: The psychometric curves and JNDs of both subjects. Each trial consisted of a reference timing and a comparison timing. The left graphs recorded subjects' responses for each trial. The comparison timing followed the simple up-down method while the reference timing remained the same for each subject (dashed line). Each subject ran the test twice to find the early timing JND and late timing JND separately. The timing difference was the difference between the comparison timing and the reference timing. All the trial data points were used to fit the psychometric curve using the maximum likelihood criterion [17], while the plots on the right column summarized trial points that had the same comparison timing.

were asked 'Are the two timings equal or different?' at the end of the second timing.

The reference timing was a constant value during the test for each subject, corresponding to their preferred timings (Table. I). The comparison timing was determined by the simple up-down method: if the answer was 'different', the comparison timing in the next trial would be a $\Delta$ ($\Delta$ = 1% stride period) closer to the reference timing; if the answer was 'equal', the next comparison timing would be a $\Delta$ further from the reference timing. A $\Delta$ was set to be 1% stride period due to the resolution in stride duration prediction. The single trial protocol is shown in Fig. 2. The initial comparison timing was 3$\Delta$ away from the reference timing. The test was conducted twice to approach the reference timing from both above and below. Therefore, two JNDs were determined for each subject, named early timing JND and late timing JND, respectively. Each test consisted of 33 trials, with 3 practice trials and 30 experimental trials.

### D. Data Analysis

The different response rate, which indicated the subjects' ability in differentiating two timings, was assessed to fit the psychometric function, which determined the just-noticeable difference (JND) threshold for each subject. Green [13] introduced a modified logistic function that was shown to be robust to non-sensory factors, such as subjects' response bias:

$$P(\text{different}) = \alpha + (1-\alpha)\frac{1}{1+e^{-k(x-m)}} \tag{2}$$

where $\alpha$ is the false-alarm rate (the probability of a 'different' response when the comparison and the reference values are the same), $k$ is the slope of the psychometric function, $m$ is the mean of the logistic and is set to be the JND. In this study, the JND represented the smallest change in actuation timing that can be reliably perceived by subjects. Lower JND values corresponded to a better perception. The overall JND was the summation of early timing JND and late timing JND. The logistic function was fitted to the data using the maximum likelihood (ML) criterion [17]. The analysis was performed in MATLAB (MathWorks, Natick, MA, USA).

## III. Results

Two subjects' preferred actuation timings were 25% and 27% stride period respectively (Table I). The JNDs of two subjects were summarized in Table II. Their performances were shown in Fig. 3. The false-alarm rate ($\alpha$) was 0.5 in the late timing perception test of subject 2, as his probability of a 'different' response was 50% (6 'different' out of 12 trials) when the reference timing and the comparison timing were equal. $\alpha$ was 0 in the other three tests.

Subject 2 exhibited higher sensitivity towards actuation timing (3.6% vs. 6.8% stride period). While subject 1 had similar JND in early and late timing (3.4% vs. 3.5% stride period), subject 2 was more sensitive to late timing change (1.4% vs. 2.1% stride period).

TABLE II: The JND of Two Subjects

| | Early Timing (% stride period) | Late Timing (% stride period) | Overall (% stride period) |
|---|---|---|---|
| Subject 1 | 3.4% | 3.5% | 6.8% |
| Subject 2 | 2.1% | 1.4% | 3.6% |

## IV. Discussion

In this pilot study, we measured subjects' perception of exoskeleton actuation timing. Results indicate the variation across subjects, but the distribution of the sensitivity across people needs to be further evaluated.

Subjects reported that sometimes it was hard to tell if the comparison timing and the reference timing were different or equal, because they felt like they were similar. It was unclear what each subject's strategy was at this situation, and this may lead to a biased response (subjects' tendency to report 'different' or 'equal' when they are not sure). The high false alarm rate ($\alpha$ = 0.5) appeared in subject 2 during late timing perception test supported the existence of response bias. The correction of false alarm rate was applied to reduce the bias but cannot fully eliminate its influence [18]. Catch trials at the reference timing can be introduced to have a better estimation of $\alpha$ in the future study [18]. However, as the signal threshold value is the major item of interest instead of other psychometric function properties such as the slope of the curve, the accuracy of $\alpha$ in this model might have little influence on the estimate of the JND threshold [13].

The error in predicting stride duration can have an influence on subjects' perception. Though human walking is a repetitive motion, there still exist differences between each gait cycle. In this study, the current stride duration is determined as the average of the previous three strides. A perfect estimation of the actual stride duration is not possible, thus influencing the real actuation timing (represented as the percentage of stride period). Though we asked subjects to take 5 strides for each timing to obtain a general feeling, this small variation might still affect subjects' perception. The selection of $\Delta$ was influenced by the stride duration prediction. While a smaller $\Delta$ would provide increased precision in estimating JND, it would require a more accurate stride duration prediction. A non-adaptive method can also be used to gain a better psychometric curve fitting, as the results of this work have provided an appropriate range of stimuli levels.

Tests on more subjects are needed in the future, including expanding the healthy population and considering the effects of gender, age, and pathology. Human ankle proprioception has been well-studied in both static and dynamic aspects (*e.g.* position, velocity). We hypothesize that differences in human intrinsic proprioception can lead to different sensitivity towards exoskeleton control parameters. Future study on the correlation between ankle proprioception and human perception of ankle exoskeletons can be important in understanding the sensorimotor control of the lower extremities.

## V. Conclusion

In this pilot study, two subjects exhibited different sensitivity towards exoskeleton actuation timing during walking. Their just-noticeable difference (JND) thresholds were 6.8% and 3.6% stride period respectively. The results from this study provide a preliminary understanding of human perception towards exoskeleton actuation timing. Users were able to perceive differences in exoskeleton timing and the perception thresholds can be different across people. Further study on more subjects to evaluate a relationship between human ankle proprioception and human perception of exoskeleton control parameters is needed for a deeper understanding of differences in human-exoskeleton performance. The results can be used to guide the design and control of wearable robotics, such as setting up the precision requirements for control parameters, allowing more smooth transitions between different parameter values, and increasing the efficiency in optimization algorithms by setting appropriate step values.

## References


[1] D. P. Ferris, "The exoskeletons are here," *Journal of neuroEngineering and rehabilitation*, vol. 6, no. 1, pp. 1–3, 2009.

[2] G. S. Sawicki, O. N. Beck, I. Kang, and A. J. Young, "The exoskeleton expansion: improving walking and running economy," *Journal of neuroengineering and rehabilitation*, vol. 17, no. 1, pp. 1–9, 2020.

[3] P. Malcolm, W. Derave, S. Galle, and D. De Clercq, "A simple exoskeleton that assists plantarflexion can reduce the metabolic cost of human walking," *PloS one*, vol. 8, no. 2, p. e56137, 2013.

[4] S. Galle, P. Malcolm, S. H. Collins, and D. De Clercq, "Reducing the metabolic cost of walking with an ankle exoskeleton: interaction between actuation timing and power," *Journal of neuroengineering and rehabilitation*, vol. 14, no. 1, pp. 1–16, 2017.

[5] P. Malcolm, R. E. Quesada, J. M. Caputo, and S. H. Collins, "The influence of push-off timing in a robotic ankle-foot prosthesis on the energetics and mechanics of walking," *Journal of neuroengineering and rehabilitation*, vol. 12, no. 1, pp. 1–15, 2015.

[6] K. A. Ingraham, C. D. Remy, and E. J. Rouse, "User preference of applied torque characteristics for bilateral powered ankle exoskeletons," in *2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)*. IEEE, pp. 839–845.

[7] R. W. Jackson and S. H. Collins, "An experimental comparison of the relative benefits of work and torque assistance in ankle exoskeletons," *Journal of applied physiology*, vol. 119, no. 5, pp. 541–557, 2015.

[8] H. Kim, L. M. Miller, Z. Li, J. R. Roldan, and J. Rosen, "Admittance control of an upper limb exoskeleton-reduction of energy exchange," in *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 2012, pp. 6467–6470.

[9] G. T. Fechner, *Elemente der psychophysik*. Breitkopf u. Härtel, 1860, vol. 2.

[10] A. F. Azocar and E. J. Rouse, "Stiffness perception during active ankle and knee movement," *IEEE Transactions on Biomedical Engineering*, vol. 64, no. 12, pp. 2949–2956, 2017.

[11] N. Elangovan, A. Herrmann, and J. Konczak, "Assessing proprioceptive function: evaluating joint position matching methods against psychophysical thresholds," *Physical therapy*, vol. 94, no. 4, pp. 553–561, 2014.

[12] M. K. Shepherd, A. M. Simon, J. Zisk, and L. Hargrove, "Patient-preferred prosthetic ankle-foot alignment for ramps and level-ground walking," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2020.

[13] D. M. Green, "A maximum-likelihood method for estimating thresholds in a yes–no task," *The Journal of the Acoustical Society of America*, vol. 93, no. 4, pp. 2096–2105, 1993.

[14] N.-j. He, J. R. Dubno, and J. H. Mills, "Frequency and intensity discrimination measured in a maximum-likelihood procedure from young and aged normal-hearing subjects," *The Journal of the Acoustical Society of America*, vol. 103, no. 1, pp. 553–565, 1998.

[15] L. M. Mooney, E. J. Rouse, and H. M. Herr, "Autonomous exoskeleton reduces metabolic cost of human walking during load carriage," *Journal of neuroengineering and rehabilitation*, vol. 11, no. 1, pp. 1–11, 2014.

[16] J. Zhang, P. Fiers, K. A. Witte, R. W. Jackson, K. L. Poggensee, C. G. Atkeson, and S. H. Collins, "Human-in-the-loop optimization of exoskeleton assistance during walking," *Science*, vol. 356, no. 6344, pp. 1280–1284, 2017.

[17] N. Prins *et al.*, *Psychophysics: a practical introduction*. Academic Press, 2016.

[18] X. Gu and D. M. Green, "Further studies of a maximum-likelihood yes–no procedure," *The Journal of the Acoustical Society of America*, vol. 96, no. 1, pp. 93–101, 1994.