Published in final edited form as:
*IEEE Robot Autom Lett*. 2017 July ; 2(3): 1495–1501. doi:10.1109/LRA.2017.2671374.

# Variable Damping Force Tunnel for Gait Training Using ALEX III

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## Abstract

Haptic feedback affects not only the quality of training but can also influence the physical design of robotic gait trainers by determining how much force needs to be applied to the user and the nature of the force. This paper presents the design of a variable damping force tunnel and explores the effect of the shape and strength of the damping field using ALEX III, a treadmill-based exoskeleton developed at Columbia University. The study consists of 32 healthy subjects who were trained for 40 minutes in the device. The subjects were trained to follow a footpath with a 50% increase in step height, so the foot would have 1.5 times the ground clearance. Subjects were assigned to one of four groups: linear high, linear low, parabolic high, and parabolic low. Linear or parabolic denotes the shape of the damping field, and high or low denotes the rate of change (strength) of the field based on error. It is shown that the new controller is capable of inducing gait adaptations in healthy individuals while walking in the device. All groups showed adaptations in step height, while only the high strength groups showed changes in normalized error area, a measure of how closely the desired path was followed.

### Index Terms

Haptics and Haptic Interfaces; Rehabilitation Robotics; Prosthetics and Exoskeletons

## I. Introduction

Robot assisted gait training (RAGT) is gaining popularity due to its ability to reduce manual effort for physical therapists, record quantitative measures of improvement, and provide patients with consistent and repeatable therapy. Even with these benefits, there have been mixed results in terms of outcomes [1]–[10]. It should be noted for most studies that showed RAGT to have greater improvements over conventional therapy, RAGT was done in addition to conventional therapy and/or was used in sub-acute populations. This may be a limitation of the therapy type which is targeted at providing assistance to the subject in completing the task. However, alternatives that are more challenging may better serve the needs of higher functioning individuals.



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Prior control strategies have fallen primarily into three categories: prescribed motion, assist-as-needed (AAN), or error enhancing. Prescribed motion was one of the earliest strategies used and consists of defining a desired motion and having the device move the person through that motion [11]–[14]. One limitation of this method is user involvement, as the wearer can remain passive in the device and not put in any effort to achieve the motion, and as a result not receive the full benefit of the training. To remedy this, AAN strategies were developed that rely on some form of user engagement to perform the task. These can vary from requiring the subject to initiate movement before the robot starts to apply force [15], [16], to those that provide limited guidance when following a path [17]–[20]. While these assist-as-needed strategies do enhance user engagement, the user may adapt to the level of assistance, and only put in as much effort as required to complete the motion. This reduced effort to increase the level of assistance from the device is referred to as “slacking”. In order to prevent this and enhance training, AAN controllers that adapt to “slacking” have been proposed that reduce the aid from the device if the person is relying too heavily on it [17]. An alternative to these approaches that aid the subject in performing the task are error-enhancing strategies. These increase the amount of error, forcing the user to actively resist the device to achieve the goal [21]–[23].

Assistive controllers have also been explored in conjunction with resistive forces. For gait, Wu et al. have developed a cable driven device capable of resisting or assisting in gait. This uses the position error to create an assistive force and the velocity error to create a resistive force [24], [25]. The Lokomat has been used with a fixed damping coefficient [26], which can also be determined before each training session based on the maximum voluntary contraction and walking speed [27].

As for movement training of the upper limb, a 2-DOF device that can simulate virtual objects with spring-damper properties using electrorheological clutches was proposed in [28]. In this work, forces were computed based on position and damping coefficients were constant. The MIT-Manus has been used with viscous force fields for perturbation, however, these did not behave as dampers, as the force applied was not in the direction of travel but rather at a predefined angle [29]–[31]. Emken and Reinkensmeyer have used a similar approach for gait training where an upward force was applied based on the horizontal velocity of the ankle [32]. Huang, Patton, and Mussa-Ivaldi have used negative damping in unimpaired individuals [33], and Huang and Patton have used the same approach with stroke survivors to improve task performance in a circle following task [34].

While these various feedback strategies have shown some benefits, the field is still in the early stages of exploration and other haptic feedback strategies may be more effective in general or for specific populations. Prior feedback methods have been primarily prescriptive in nature, providing information as to what needs to be done to correct error through forces related to the direction of error [35], [36]. Descriptive feedback would instead only provide information on the error but no indication as to how to correct the error. This requires the individual to explore movements to find those that reduce the error.

The current paper will present a new type of haptic feedback and provide a proof of concept using healthy individuals. This new haptic feedback which resists motion as opposed to directing the ankle towards or away from the path, utilizing the hypothesis that humans are trying to minimize their energy expenditure during walking. This is done through the use of a viscous damping field, which represents a more descriptive form of knowledge of performance by describing the magnitude of the error but provides no information on how to correct it. The purpose of this study is to test two hypotheses: 1) If an error based damping field is applied during gait training, then subjects will adapt to the new gait pattern. 2) If a damping field changes more gradually, then the subject will adapt better to the trained gait pattern.

The next section will present this novel feedback strategy. This will be followed by the experimental setup and the results of a study used to validate the strategy on healthy young adults. To the best of the authors' knowledge, the use of a variable damping field based on position error is largely unexplored.

## II. Haptic Feedback Design

The current controller is built from prior work using force tunnels [18], [20], [23], [37]–[39]. Now, as the distance outside the tunnel increases, the damping coefficient applied to the foot increases till it reaches saturation:

$$B_{\text{linear}}=\begin{cases} B_1 \times (|d| - D_0/2) & \text{if } |d| \geq D_0/2 \\ 0 & \text{if } |d| < D_0/2 \end{cases} \quad (1)$$

$$B_{\text{parabolic}}=\begin{cases} B_2 \times (|d| - D_0/2)^2 & \text{if} |d| \geq D_0/2 \\ 0 & \text{if} |d| < D_0/2 \end{cases} \quad (2)$$

$$\mathbf{F}=\begin{cases} -B \times \mathbf{V_{ankle}} & \text{if } B \leq B_{\max} \\ -B_{\max} \times \mathbf{V_{ankle}} & \text{otherwise} \end{cases} \quad (3)$$

Here **F** is the Cartesian force vector applied at the ankle and $\mathbf{V_{ankle}}$ is the Cartesian velocity vector of the ankle. $D_0$ is the tunnel width and $d$ is the distance of the current ankle point from the desired path. $B_1$ and $B_2$ are the damping coefficient gains for the linear and parabolic fields respectively, Fig. 1. $B$ is the damping coefficient and is calculated from (1) or (2), depending on the desired shape of the field. $B_{max}$ is the saturation point for the damping coefficient.

## III. Study Protocol

Thirty-two right leg dominant, healthy individuals, with no neurological or physical impairments that would affect their ability to walk in the device or adapt to new gait patterns were recruited (Table I). Each subject performed a single testing session using the ALEX III device, Fig. 2. Details of the device have been previously presented [20], [40]. Subjects were separated by gender, and randomly assigned to one of four groups, linear low ($B_1$ = 1732$N$ $s/m^2$), linear high ($B_1$ = 2389$N\,s/m^2$), parabolic low ($B_2$ = 200012$N\,s/m^3$), and parabolic high ($B_2$ = 380340$N\,s/m^3$). Corresponding to the rate of increase of the damping coefficient, (1) and (2). The saturation point was set, for safety, to a value at which healthy individuals would still be able to complete a step ($B_{max}$ = 15$N\,s/m$). For consistency with prior work, the values for $B_1$ and $B_2$ were selected so the distance from the desired path where saturation occurred was the same distance as in previously used strategies [41]. This was done to determine which setting should be used for future experiments and to evaluate the effectiveness of the feedback strategy. It was hypothesized that a more gradual change in the damping field would make it easier for subjects to feel the damping gradient. Using the gradient, subjects could determine how to attain the target path. Additionally, more gradual changes would allow them to feel the gradient at a larger distance from the target path prior to saturation.

Each session, Table II, began by finding the subject's comfortable walking speed in the device. Next, the subject walked for ten minutes to acclimate to walking in the device. After a break, a five minute baseline bout was performed to record their normal walking in the device. The average baseline footpath was then modified to create a footpath with a 50% increase in step height in early swing. This new path was the target path used in training. An increase in step height was chosen as stroke survivors typically have difficulty achieving foot clearance, and as a result, many will be trained to a gait pattern with an increased step height. This approach has previously been used in healthy individuals for this reason [23], [42].

Subjects then performed four ten minute training bouts with the damping field applied to their left leg and intermittent visual feedback, alternating on/off every 2.5 minutes (50% frequency). It has been established that continual feedback can be detrimental to retention as individuals will depend on the feedback to correct their actions [35]. Kim et al. have previously shown that providing intermediate visual feedback with haptic guidance improves adaptation and retention over haptic or visual feedback alone [43].

Each training bout was followed by a thirty second catch-trial, a one minute break, and one minute mid-test, all without force or visual feedback. Catch trials began with the first step immediately following the removal of the force to capture the response to the removal of the force feedback. The last catch trial was followed by a one minute break and a 5 minute post-test instead of a one minute mid-test. Two more post-tests followed with five minute breaks separating them. All post-tests were performed without force or visual feedback. During training, subjects were given verbal encouragement when they were performing the task well. Subjects were instructed before training to walk in the way that they were trained for the mid-tests, i.e. when the force was removed. Subjects were given no specific directions regarding how to walk during post-tests.

## A. Data Analysis

Analysis was performed on both the normalized error area (NEA) and the normalized step height (NSH) of the mean path for the session, Fig. 3. The NEA is the area between the average path for the session, $P_{session}$, and the target path, $P_{target}$, divided by the area between the baseline path, $P_{baseline}$, and the target path:

$$\mathrm{NEA}=\frac{P_{\mathrm{session}} \oplus P_{\mathrm{target}}}{P_{\mathrm{baseline}} \oplus P_{\mathrm{target}}} \quad (4)$$

This provides a measure of how well the overall path was followed [44]. Values closer to zero indicate that the target path was followed more closely, values less than one indicate that the subject was closer to the target path than they were during their baseline session. The NSH takes the maximum ankle height, $y_{session}$, minus the minimum ankle height of the session's mean path and divides it by the same value calculated from the baseline path, $y_{baseline}$:

$$\mathrm{NSH}=\frac{\max(y_{\mathrm{session}})-\min(y_{\mathrm{session}})}{\max(y_{\mathrm{baseline}})-\min(y_{\mathrm{baseline}})} \quad (5)$$

This gives a measure of how well the subjects were able to achieve the dominant feature of the path, the increase in step height. A value of 1 has the same step height as baseline whereas a value of 1.5 has the same height as the target path.

One-sample t-tests were performed on both dependent variables by pooling the values for all three post-tests for each subject to evaluate if their mean was significantly different from 1, and the Bonferroni-Holm correction was applied. The value of one was used for comparison for both tests as it indicates baseline performance. Next, repeated measures ANOVA was performed on the posttest sessions with session as the within-subject factor and strength and shape as the between-subject factors. If Mauchly's Test of Sphericity indicated that the sphericity assumption had been violated, the appropriate correction was applied. This test was to indicate if there was any degradation of performance over time, and to determine if there was an effect of strength or shape. Repeated measures ANOVA was performed in the same way on the training sessions, to examine if there was a change in how the subjects responded to the damping field. For all tests, $\alpha = 0.05$.

## IV. Results

The results of the one sample t-test can be found in Table III. The groups with high damping coefficient gains showed statistically significant differences from 1 in NEA. All groups showed statistically significant differences from 1 in NSH. The NEA and NSH for the post training evaluations can be seen in Fig. 4 and Fig. 5. The NEA and NSH for the training sessions can be seen in Fig. 6 and Fig. 7.

For the repeated measures ANOVA of the NEA of the mean, in the post-tests, path Mauchly's Test of Sphericity indicated that the sphericity assumption had been violated, $\chi^2(2) = 8.9$, $p = 0.012$, so the Huynh-Feldt correction, $\varepsilon = 0.91$, was applied. There was no main effect of session, $F(1.81, 50.8) = 0.37$, $p = 0.673$. Analysis of the between subject factors revealed the null hypothesis for strength could be rejected $F(1, 28) = 5.10$, $p = 0.032$, but could not be rejected for shape, $F(1, 28) = 2.32$, $p = 0.139$. Subjects in the high strength groups had significantly lower normalized error area, and from the one sample t-tests both were significantly different from one.

For the repeated measures ANOVA of the NSH of the mean path, in the post-tests, Mauchly's Test of Sphericity indicated that the sphericity assumption had been violated, $\chi^2(2) = 15.6$, $p < 0.001$, so the Greenhouse-Geisser correction, $\varepsilon = 0.70$, was applied. There was no main effect of session, $F(1.39, 38.9) = 2.72$, $p = 0.095$. Analysis of the between subject factors revealed the null hypothesis could not be rejected for strength, $F(1, 28) = 0.03$, $p = 0.867$, or shape, $F(1, 28) = 0.22$, $p = 0.641$.

For the repeated measures ANOVA of the NEA of the mean path, in the training session, Mauchly's Test of Sphericity indicated that the sphericity assumption had been violated, $\chi^2(5) = 30.7$, $p < 0.001$, so the Greenhouse-Geisser correction, $\varepsilon = 0.61$, was applied. There was no main effect of session, $F(1.81, 50.8) = 1.23$, $p = 0.299$. Analysis of the between subject factors revealed that the null hypothesis for the strength by shape interation could be rejected, $F(1, 28) = 5.43$, $p = 0.027$. As a result, separate analyses were run for both the linear and parabolic shaped fields using repeated measures ANOVA. Mauchly's Test of Sphericity indicated that the sphericity assumption had been violated for both linear, $\chi^2(5) = 22.9$, $p = 0.001$, and parabolic shapes, $\chi^2(5) = 11.2$, $p = 0.049$, so the Greenhouse-Geisser correction was applied, linear $\varepsilon = 0.51$, and parabolic $\varepsilon = 0.72$. Again, no effect for session was found, linear $F(1.54, 21.6) = 0.863$, $p = 0.409$, and parabolic $F(2.15, 30.0) = 0.641$, $p = 0.544$. For the analysis of the linear group no effect of strength was found, $F(1, 14) = 1.48$, $p = 0.244$. For the analysis of the parabolic group there was an effect for strength, $F(1, 14) = 4.81$, $p = 0.046$.

For the repeated measures ANOVA of the NSH of the mean path, in the training session, Mauchly's Test of Sphericity indicated that the sphericity assumption had not been violated, $\chi^2(5) = 10.07$, $p = 0.074$. There was no main effect of session, $F(3, 84) = 2.24$, $p = 0.091$. Analysis of the between subject factors revealed the null hypothesis could not be rejected for strength, $F(1, 28) = 0.198$, $p = 0.660$, or shape, $F(1, 28) = 0.068$, $p = 0.447$.

## V. Discussion

All groups increased their step height as a result of training, and this did not significantly degrade during the 26 minutes of post-test. This change was not significantly affected by the strength or shape of the field. This indicates that subjects are able to adapt to the coarse shape of the target. However, any effect of shape or strength had a smaller effect size than this study could detect.

Only the high strength groups showed adaptation in terms of NEA, and this was significantly different from the low strength groups. This indicates that the faster rate of change of the damping coefficient improved the adaptation to the finer details of the foot path. From this, it appears the original hypothesis, that a more gradual change in the damping field would allow subjects to follow and retain the path better, was not correct. The effect may not be as simple as a faster change in damping coefficient produces better results. Alternatively, the effect may not be a result of the rate change, but could be an effect from decreasing the distance from the path where the tunnel saturates. While not statistically significant, the parabolic low group did have better performance with respect to NEA than the linear low group. This trend indicates that the rate of change may be more important than the saturation point, as both low groups saturated at the same distance from the path but the parabolic low group had a faster rate of change as it approached saturation. Although, due to the lack of significance, this statement needs further validation to confirm.

The parabolic high group most closely maintained the path during training, as shown by the lower NEA values. While training performance does not necessarily translate to retention in the post-tests, in this case it does not appear to be detrimental. This greater performance during training combined with the adaptation in both NEA and NSH, indicates that of the given choices of parameters for training the parabolic high set produces a good combination of performance during both training and post-tests. This is likely due to the rate of change of the damping field being the greatest for this group, and as a result these subjects may have had a greater focus on the overall path shape, and not simply on the increase in step height. With this in mind it may be worth exploring the extreme case of saturation at the tunnel width, as would be the case with a step function, to examine if this is sufficient to achieve adaptation. This should be explored in both the Cartesian and joint space.

The use of resistance training with gait has been show to increase speed and balance in individuals with spinal cord injuries (SCI) [24], and can improve knee flexion [26], [27]. These studies indicate that some populations may benefit from resistive forces. Whether this can be enhanced by variable viscous damping remains an open question. Studies in unimpaired individuals using AAN strategies have shown similar performance in terms of path following, although differences in methods prevent direct comparison [44], [45]. The damping field had a similar magnitude of adaptation during the first ten minute following training when compared to tests using a similar target path for both error-enhancing and AAN strategies [23]. A validation of the variable damping field for stroke survivors, as well as a direct comparison to error-enhancing and AAN strategies in unimpaired individuals are currently planned, now that this new strategy has been validated.

If simple step functions in joint space are effective, exoskeletons for gait training could be as simple as a rotary damper and a clutch which engages the damper when the subject is outside of the prescribed tunnel. Alternatively generators which could be bypassed when the subject is inside the tunnel could replace the dampers. In this configuration, rather than generating heat, the energy removed from the system could power the electronics. These, in turn, would only need to determine position and engage/disengage the generators, and this would require very little power. The batteries could then be smaller and lighter, as they would frequently be recharged, or they could potentially be replaced entirely by capacitive storage. Regardless of the use of step responses, this move to dissipative forces could have a drastic impact on exoskeleton design for rehabilitation, as they reduce the device’s dependence on its power source, which currently either require devices to be tethered or to carry large batteries with them. By dissipating power, an untethered device which can run all day is within the realm of possibility. This can result in devices that easier to use and also means that therapy can potentially move outside of the clinic and be applied for longer duration. However, this method must first be validated in populations in need of rehabilitation.

This study was performed on a relatively small set of subjects and as a result may not have had sufficient power to detect differences with a small effect size resulting in type II errors. With a larger study the parabolic low group may show adaptation in NEA and an effect for session may appear. Subjects were also given no specific instructions about what to do during the post-tests. This lack of direction had been intended to encourage subjects to walk without trying to follow a specific path, in order to look for inherent adaptation. However, in the future we will provide explicit instructions to prevent ambiguity and reduce variability in subject performance. Additionally, the results from this study may not apply to stroke survivors, who may not be able to walk in this type of damping field, or who may adapt differently to the force. It is likely that severely impaired individuals will not be able to tolerate this type of feedback. However, non-ambulatory individuals are currently better served by current forms of RAGT, than ambulatory individuals [10]. Damping fields are likely more appropriate for these higher functioning individuals. Although, it is still unknown if the damping field is more beneficial for these individuals than traditional RAGT, and this can only be determined through further testing. An additional concern for stroke and other neurological conditions is spasticity. If performed in conjunction with stretching it is not anticipated that this new feedback modality will increase spasticity, as while there is limited research done on strength training’s impact on spasticity, the work that has been done indicates that it does not increase spasticity [46].

## VI. Conclusion

This paper presented a new haptic feedback strategy for robot assisted gait training, based on variable viscous damping. The controller was able to induce gait changes in healthy individuals, which lasted at least 25 minutes following training. Increasing the rate the damping coefficient changes with the distance from the path improved the subjects’ ability to closely follow the path. However, increasing the strength did not have a significant effect on how well subjects were able to achieve the main feature of the path, i.e. the step height. The shape of the damping field does not play a significant role in the performance, although there are some trends which may have a smaller effect size than could be determined with the current study. This primary finding informs what parameters will be used in future studies with this feedback type.

The exploration of new types of feedback can potentially improve physical therapy and recovery from injury and change the architecture of rehabilitation robots. Proving the effectiveness of damping force fields could potentially dictate major design changes in future robotic gait trainers that will not require large electrical motors to provide forces, but could instead use variable dampers such as magnetorheological dampers, variable dashpots, electrostatic brakes, or even simple brakes with small engagement motors. Alternatively, regenerative braking could be used so that the device powers itself with only small energy storage requirements. Finally, this new type of feedback strategy may be able to better serve individuals that have not previously responded well to RAGT, by providing a more challenging training modality.

## Acknowledgments

The authors would like to thank Steve Beard, Dave Cowgill, Al Lance, Mohamed Haroun, and Robert Stark for their help with fabrication of the device. Additionally, this study would not be possible without the time volunteered by the study participants. This work was supported in part by the the National Robotics Initiative program from National Science Foundation under grant NSF IIS-1339666, NYS Contracts DOH01-C30828GG-3450000 and C31290GG.

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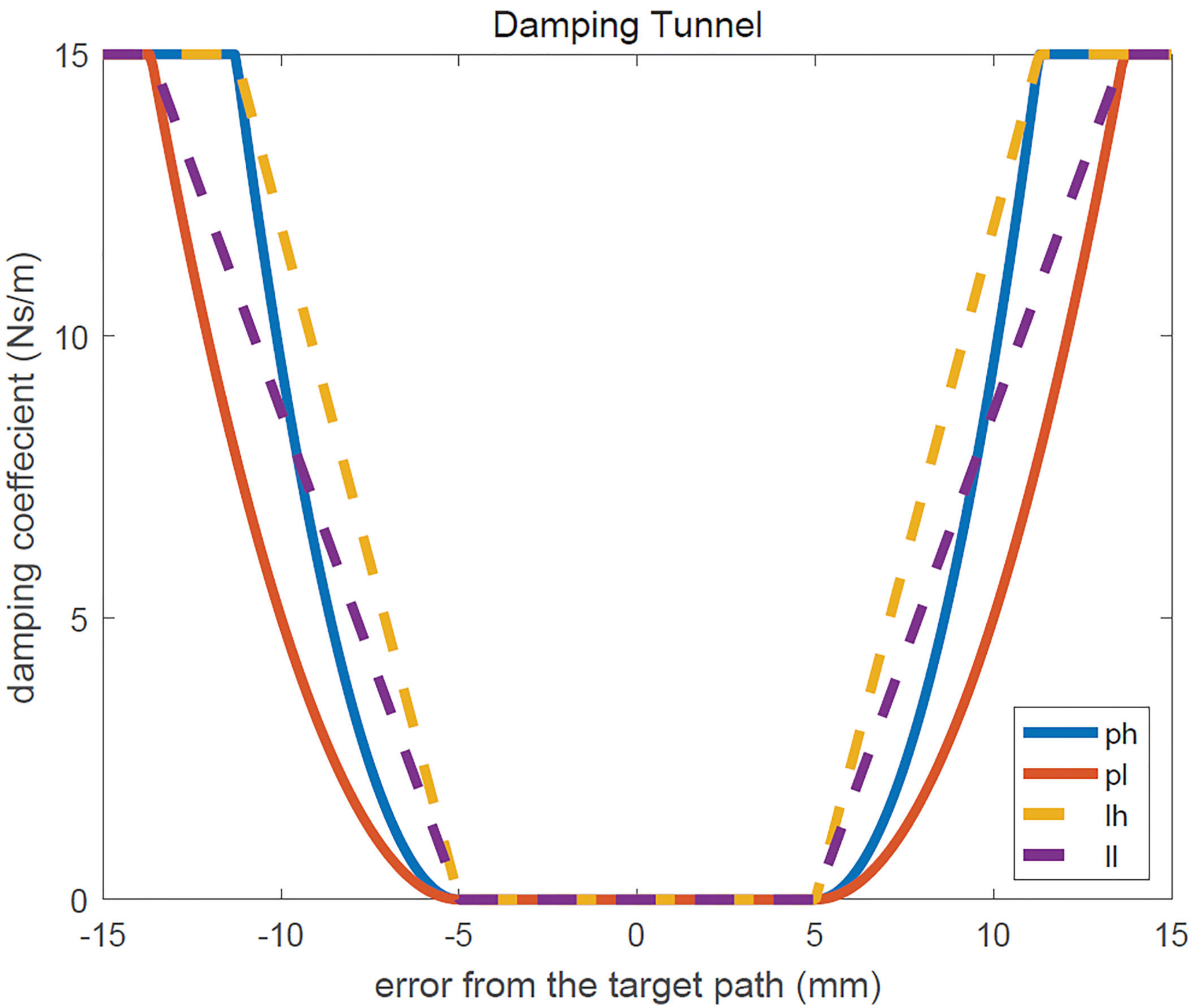


**Fig. 1.**

Damping fields used in the experiment. The damping fields used in the study are identified as ph, pl, lh, and ll for parabolic high, parabolic low, linear high, and linear low, respectively.

**Fig. 2.**
Researcher walking in ALEX III.

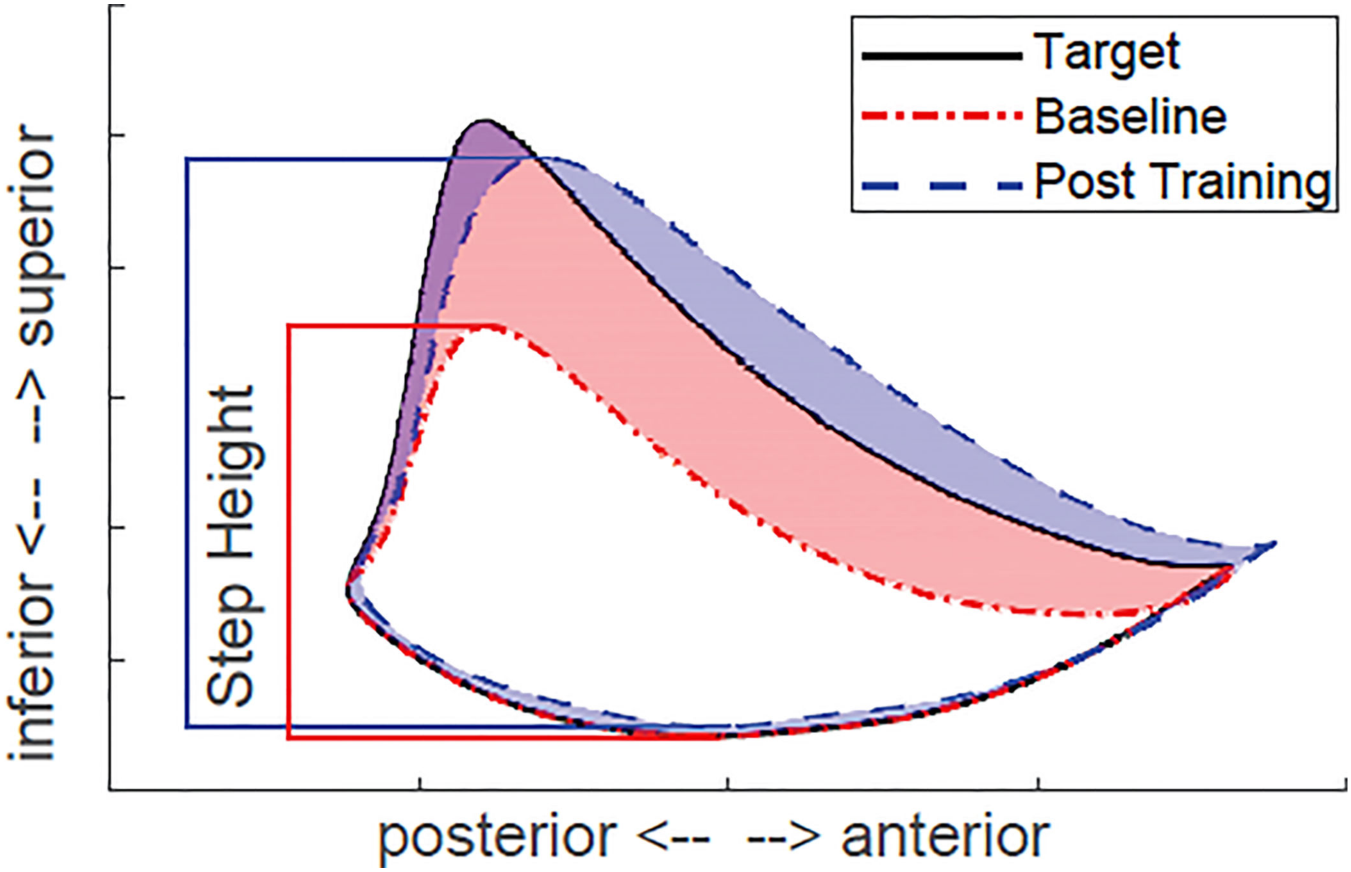


**Fig. 3.**

Representation of the areas and heights used for calculations of the Normalized Error Area and Normalized Step Height. Values are calculated based on the average ankle path of the session being evaluated. Step height for a curve is defined as $max(y) - min(y)$. Area between curves are defined as $P_1 \oplus P_2$ where $P_1$ and $P_2$ are the two ankle paths and $\oplus$ denotes the xor operator.

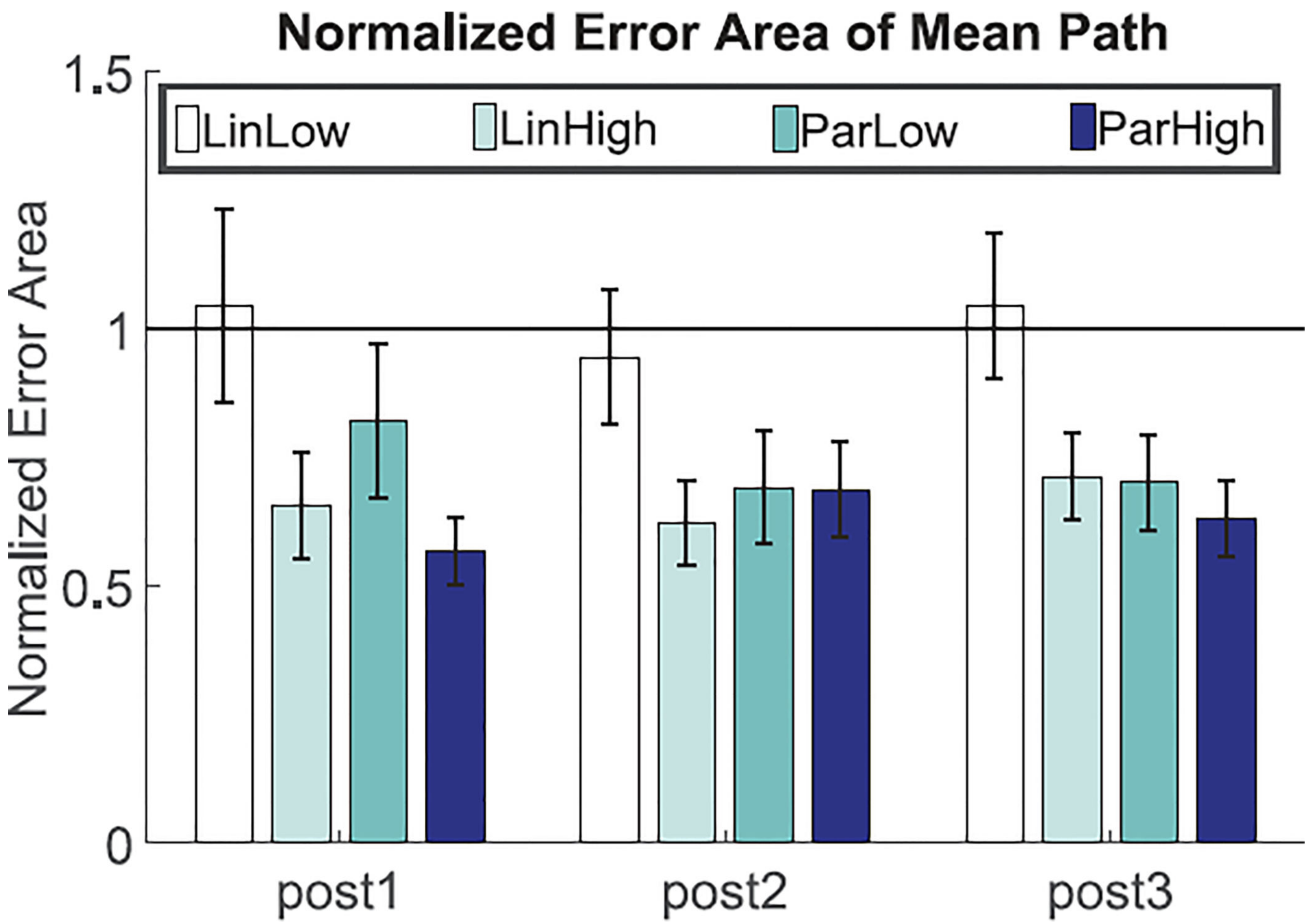


**Fig. 4.**
The normalized error area of the post-test evaluations, with the standard error shown.

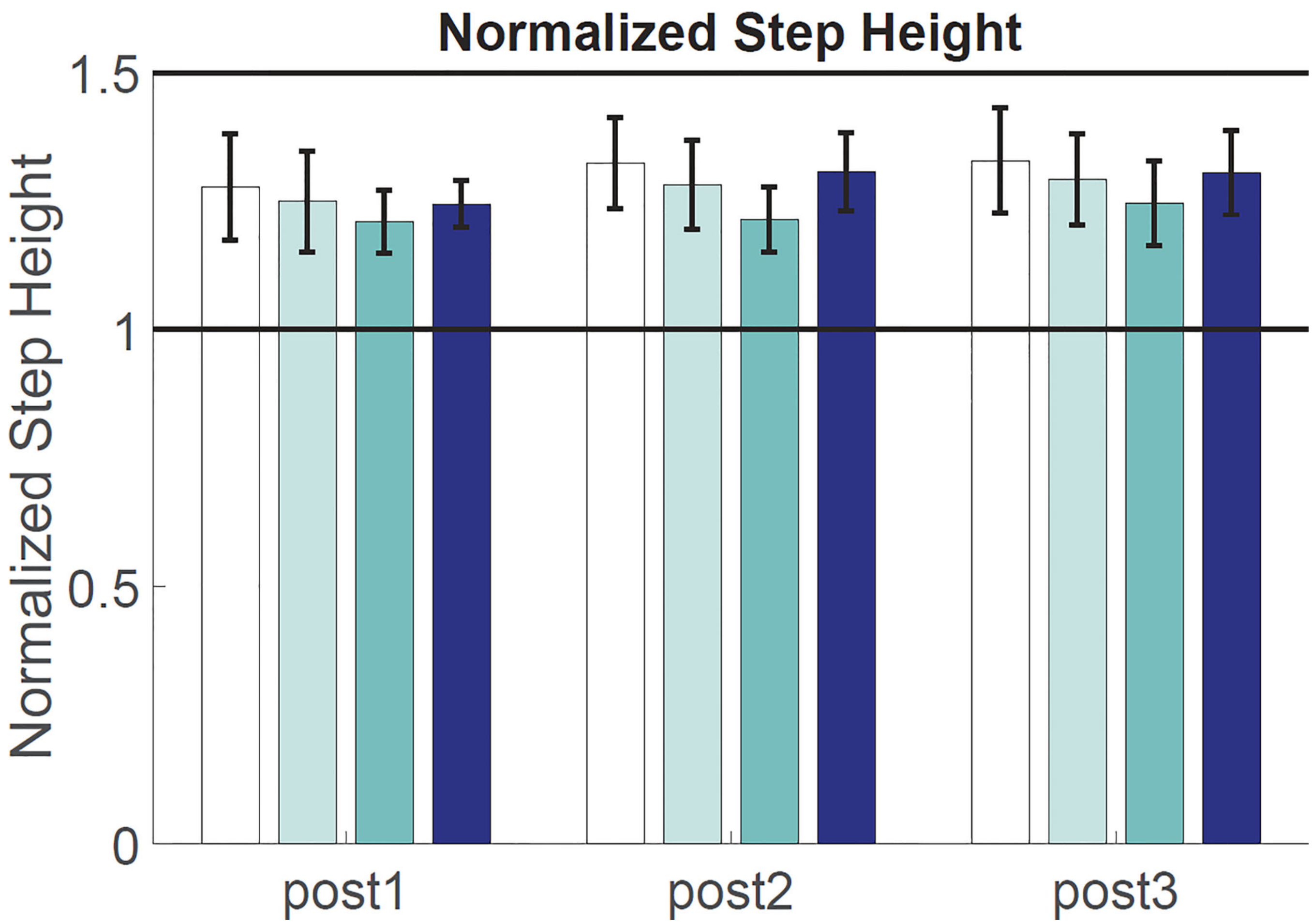


**Fig. 5.**

The normalized step height of the post-test evaluations, with the standard error shown.

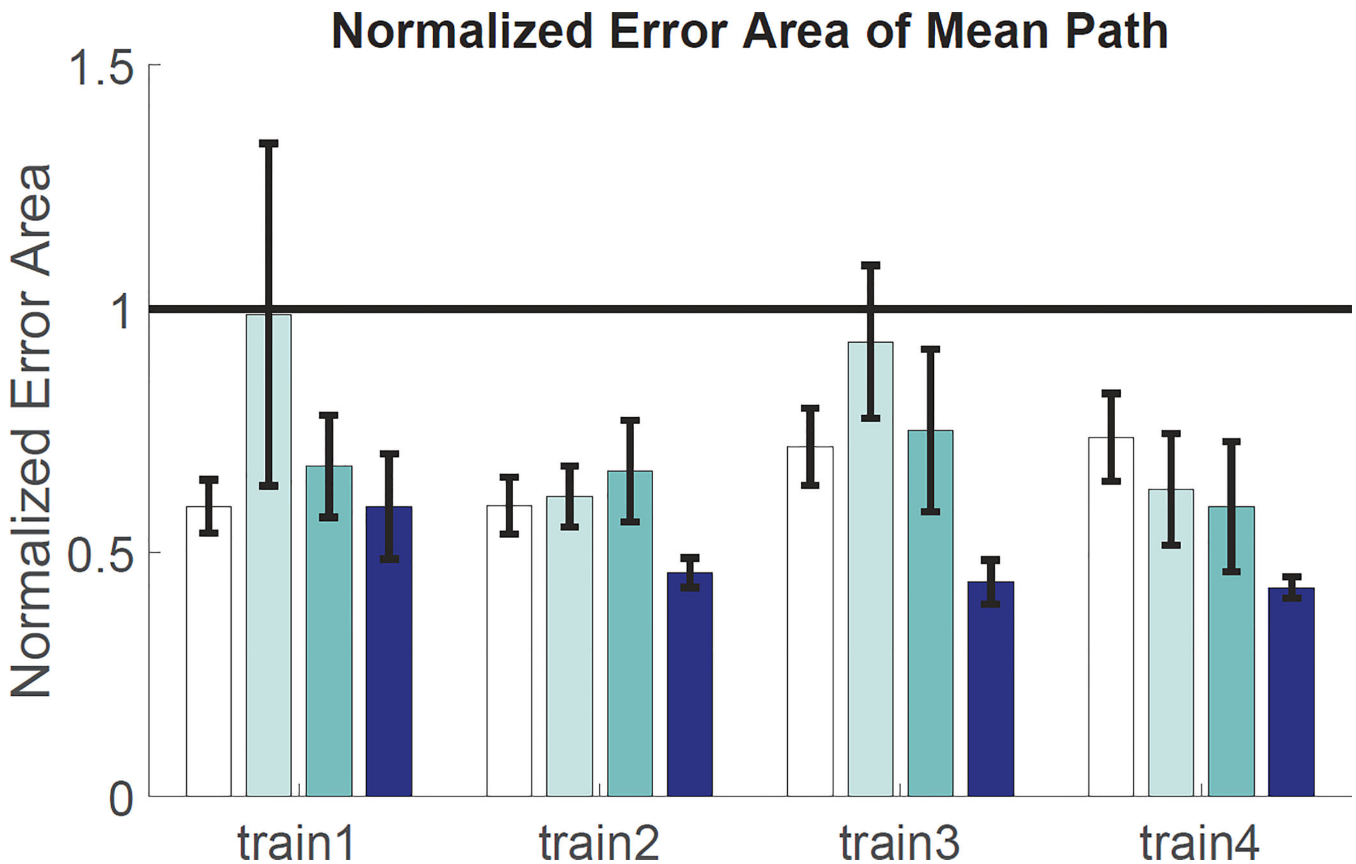


**Fig. 6.**
The normalized error area of the training sessions, with the standard error shown.

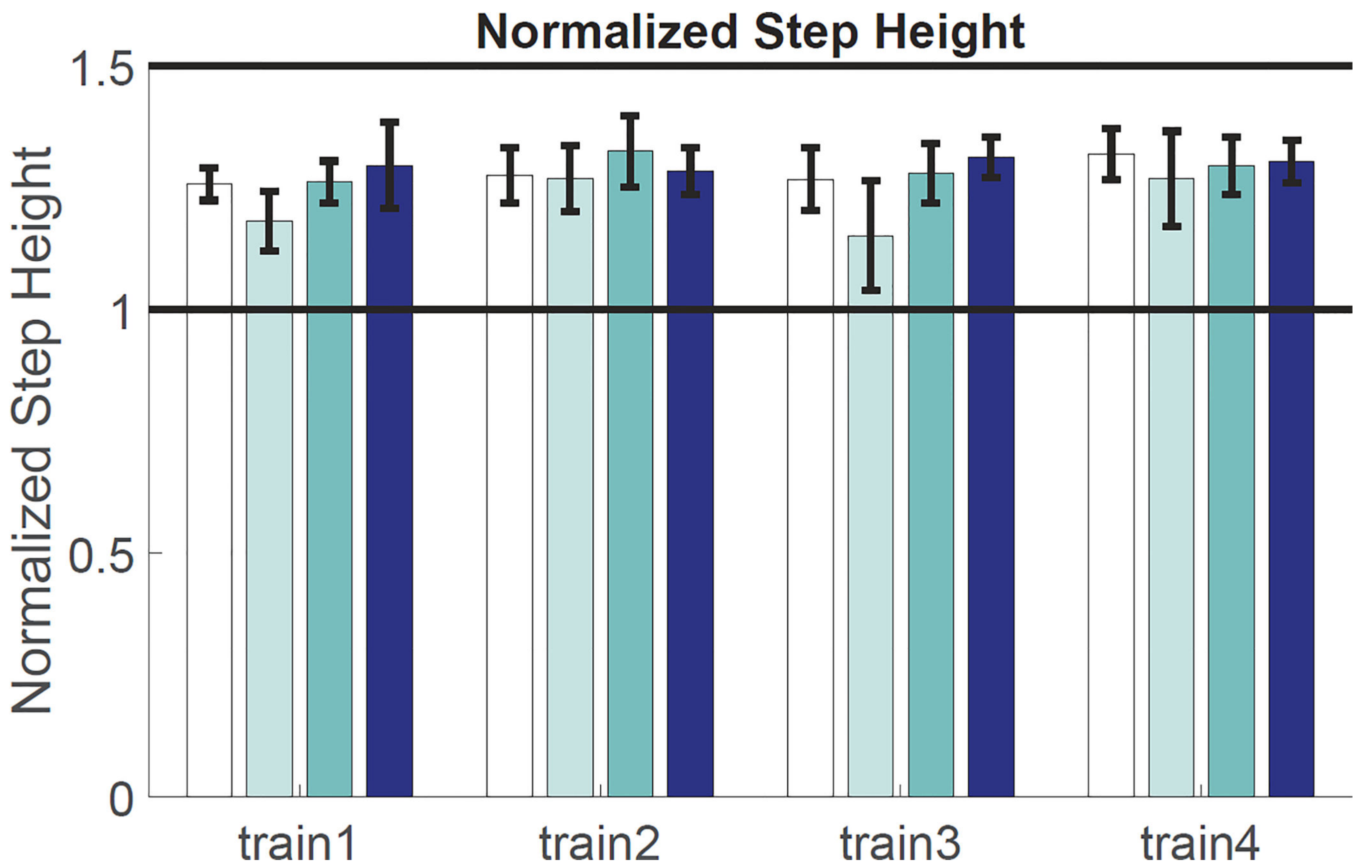


**Fig. 7.**
The normalized step height of the training sessions, with the standard error shown.

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**TABLE I**

Subjects Information

| Group | Sex | Age (yrs) | Mass (kg) | Height (m) |
|---|---|---|---|---|
| Lin Low | 6 M, 2 F | 24.1±5.1 | 73.0±9.9 | 1.80±0.06 |
| Lin High | 5 M, 3 F | 27.6±4.7 | 81.5±17.8 | 1.79±0.08 |
| Par Low | 6 M, 2 F | 25.5±4.4 | 80.0±21.1 | 1.77±0.09 |
| Par High | 5 M, 3 F | 21.6±2.6 | 69.1±9.1 | 1.75±0.08 |

## TABLE II

Protocol

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Adaptation | 10 min | Training 1 | 10 min | Training 2 | 10 min | Training 3 | 10 min | Training 4 | 10 min | Post-test 1 | 5 min |
| Break | 2–5 min | Catch 1 | 30 sec | Catch 2 | 30 sec | Catch 3 | 30 sec | Catch 4 | 30 sec | Break | 5 min |
| Baseline | 5 min | Break | 1 min | Break | 1 min | Break | 1 min | Break | 1 min | Post-test 2 | 5 min |
| Break | 2–5 min | Mid-test 1 | 1 min | Mid-test 2 | 1 min | Mid-test 3 | 1 min | | | Break | 5 min |
| | | Break | 2–5 min | Break | 10 min | Break | 2–5 min | | | Post-test 3 | 5 min |

## TABLE III

Statistics Table for Pooled Post-Test Sessions

| Group | Normalized Step Height | t(7) | Corrected p |
|---|---|---|---|
| Lin Low | 1.31± 0.27 | 3.21 | **0.030** |
| Lin High | 1.27± 0.25 | 3.15 | **0.016** |
| Par Low | 1.31± 0.19 | 3.40 | **0.035** |
| Par High | 1.29± 0.18 | 4.52 | **0.011** |
| **Group** | **Normalized Error Area of Mean Path** | **t(7)** | **Corrected p** |
| Lin Low | 1.01± 0.41 | 0.08 | 0.942 |
| Lin High | 0.66± 0.20 | −4.70 | **0.007** |
| Par Low | 0.74± 0.29 | −2.52 | 0.080 |
| Par High | 0.63± 0.17 | −6.14 | **0.002** |