american physiological society

JNP JOURNAL OF NEUROPHYSIOLOGY

J Neurophysiol 130: 931–940, 2023.
First published August 16, 2023; doi:10.1152/jn.00214.2023

RESEARCH ARTICLE

Control of Movement

Improvement of speed-accuracy tradeoff during practice of a point-to-point task in children with acquired dystonia

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Abstract

The tradeoff between speed and accuracy is a well-known constraint for human movement, but previous work has shown that this tradeoff can be modified by practice, and the quantitative relationship between speed and accuracy may be an indicator of skill in some tasks. We have previously shown that children with dystonia are able to adapt their movement strategy in a ballistic throwing game to compensate for increased variability of movement. Here, we test whether children with dystonia can adapt and improve skills learned on a trajectory task. We use a novel task in which children move a spoon with a marble between two targets. Difficulty is modified by changing the depth of the spoon. Our results show that both healthy children and children with acquired dystonia move more slowly with the more difficult spoons, and both groups improve the relationship between speed and spoon difficulty following 1 wk of practice. By tracking the marble position in the spoon, we show that children with dystonia use a larger fraction of the available variability, whereas healthy children adopt a much safer strategy and remain farther from the margins, as well as learning to adapt and have more control over the marble's utilized area by practice. Together, our results show that both healthy children and children with dystonia choose trajectories that compensate for risk and inherent variability, and that the increased variability in dystonia can be modified with continued practice.

NEW & NOTEWORTHY This study provides insights into the adaptability of children with dystonia in learning a point-to-point task. We show that these children adjust their strategies to account for increased difficulty in the task. Our findings underscore the potential of task-specific practice in improving motor skills and show higher level of signal-dependent noise can be controlled through repetition and learned strategies, which provides an avenue for the quantitative evaluation of rehabilitation strategies in this challenging group.

dystonia; Fitts' law; motor learning; risk aware control; speed-accuracy tradeoff

INTRODUCTION

The speed-accuracy tradeoff known as Fitts' law is ubiquitous in human movement (1). This law is typically formulated as a relationship between the speed of movement and the endpoint accuracy following a rapid or ballistic movement to the target (1, 2). Although many possible explanations have been proposed, one of the more enduring possibilities is that the tradeoff represents compensation for activity-dependent noise (signal-dependent noise), so moving more slowly may reduce noise and permit increased accuracy (2–7).

More recently, it has been shown that Fitts' law also applies in tasks where the accuracy of the trajectory matters rather than only the accuracy at the final target (6). Moreover, the quantitative relationship between speed and accuracy for any individual may be modifiable by practice, suggesting that this relationship may be related to the skill of performance in trajectory-following tasks. A trajectory-following task involves a prespecified movement and

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Submitted 24 May 2023 / Accepted 20 July 2023

may not fully capture the subject's ability to plan a trajectory (2, 6). Therefore, we have developed a novel task in which subjects must transport a marble in a spoon from one target to another (6). By varying the depth of the spoon, the task can be made difficult, and subjects are free to choose not only the speed of movement but the complete velocity profile of the trajectory to reach the target as rapidly as possible. The size of the target is not varied, so the choice of trajectory is entirely determined by the spoon's difficulty. We have previously shown that this task exhibits a robust speed-accuracy tradeoff (6), that is, the participants slow down in performing the more difficult tasks to not drop the marble.

Previous work has shown that the speed-accuracy tradeoff for a trajectory-following task can be modified with practice (2, 6, 8). Here, we test whether this tradeoff can also be modified by practice for the marble-spoon task by analyzing the marble trajectory in the spoon area. We test this in both healthy children and children with acquired dystonia (9, 10). Dystonia is a disorder characterized by increased variability of movement and increased signal-dependent noise (5, 6, 9–11). Children with dystonia are aware of their increased noise and compensate appropriately in a ballistic target task (3–6, 12). Here, we test how children in these two groups with different levels of signal-dependent noise adapt to the trajectory-following task by investigating if they adapt their strategy to lower the risk of movement (13, 14). We also compare how performance in the two groups is affected by learning during practice over a period of 5 days.

MATERIALS AND METHODS

Subjects

A total of 21 children and adolescents (aged 15.5 ± 3.4 yr) performed the study with their preferred (dominant or less dystonic) arm. Eight (5 females and 3 males) were healthy subjects, while 13 (1 female and 12 males) were diagnosed with acquired dystonia. Subjects were diagnosed by a pediatric movement disorder specialist using standard criteria in Children's Hospital, Los Angeles (CHLA), and in IRCCS Medea, Italy (15). All patients provided signed informed consent for Health Insurance Portability and Accountability Act (HIPAA) authorization if they were recruited in CHLA for the research use of protected health information. Parents of participants recruited at IRCCS Medea signed a written informed consent. The protocol of the study was approved by the IRB and the Ethical Committees of the Scientific Institute E. Medea (Reference Number: 054/14-CE; Date: 01-04-2015) and CHLA (Reference Number: CCI-11-00002). The experiments took place in two locations, the University of Southern California (USC), and IRCCS Medea. Details of the participants with dystonia are provided in Table 1.

Experimental Setup and Testing

Participants were seated upright on an adjustable chair or their own wheelchair. A board with two targets was placed on a desk in front of them. Each target was bounded by two plastic blocks and the distance between the center lines of these targets was 20 cm along the vertical axis (6) (Fig. 1*A*). The board's position was adjusted in a way that the subjects had to extend their arm fully to reach the more distant target (Fig. 1*B*). To track the spoon and upper body movement two different systems were used.

At USC, four Vicon Nexus 1.8.5 motion capture cameras (Vicon Motion Systems Ltd., UK) were used to track the spoon and upper body movements. Cameras were placed in four spots in front of the subject and were calibrated using a calibration wand to make sure they could detect all the markers. At Medea, eight optoelectronic cameras by BTS Bioengineering were placed around the subject, calibrated with a calibration wand, to track the spoon and upper body movements. Twelve passive reflective markers were attached to the upper extremity joints and body as shown in Fig. 1*B*. Two additional untethered spherical markers were used, one attached to the spoon and the other as the marble carried by the spoon (a total of 14 markers). The subjects were instructed to hold the reflective marble in the spoon and move the spoon back and forth between the two targets as fast as they could without dropping the marble. The upper extremity kinematic data along with the spoon and marble trajectory were recorded at 100 Hz in USC or 60 Hz in Medea to evaluate the participants' motor performance.

Nine different circular spoons of varying depths were designed in SolidWorks 2016 (Dassault Systems SOLIDWORKS Corporation) and were 3-D printed. The detail of their size is provided in Table 2 and the index of difficulty (ID) (1) for each

Table 1. *Patients' demographics*

Subject	Diagnosis	Tested Arm	Tested Arm BAD Score
*S1**	Generalized dystonia due to hypoxic ischemic event	L	3
S2	Chorea with underlying dystonia	R	2
S3	Generalized dystonia s/p selective dorsal rhizotomy	L	3
S4	Left-side dystonia due to mild periventricular leukomalacia (PVL)	L	1
S5	Generalized dystonia; cerebral palsy	R	3
S6	Generalized dystonia due to delayed C-section for maternal eclampsia	R	3
S7	Encephalitis	R	3
S8	Dyskinetic tetraplegic cerebral palsy due to ischemic injury	R	3
S9	Generalized dystonia; ADEM	R	3
S10	Emergency C-section; generalized dystonia	L	3
S11	Generalized dystonia; cerebral palsy	R	3
S12	Generalized dystonia; cerebral palsy	R	2
S13	Encephalitis	L	3

Participants are 8–20 yr old, including 12 males and 1 female subject. BAD, Barry–Albright Dystonia scale; L, left arm; R, right arm. **Subject 1* had deep brain stimulation electrodes in place; however, it was off during the experiment.

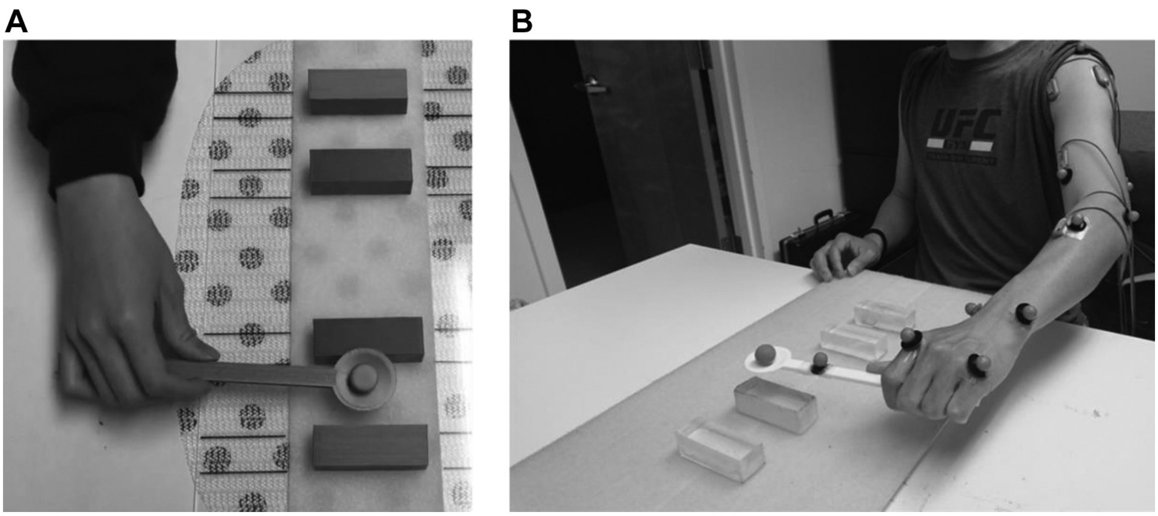

Figure 1. Experiment setup. *A*: two plastic blocks are attached to the board for each target, the distance between center lines of targets is 20 cm along the vertical axis. *B*: 12 passive reflective markers were placed on the upper limb as shown with an additional marker attached to the spoon and another one as the marble carried by the spoon. The participants were asked to extend their arm and the board position was adjusted in a way that the spoon was aligned with the distant target.

spoon was calculated based on the spoon dimensions. For each spoon, we calculate the "index of difficulty (ID)" as the ratio of the spoon's inner diameter to its depth, noting that the marble size and the spoon diameter is constant. Therefore, the ID is only dependent on the depth of each spoon. Note that unlike in standard Fitts' law formulations (1), the ID used here reflects a property of the spoon, not a property of the target (e.g., target size or distance) (6). Furthermore, while increasing ID reflects the task difficulty at a given speed, there is no simple relationship between ID and performance across all subjects, in part because there is a ceiling effect for the easiest spoons, and some subjects are unable to perform the task at all for the hardest spoons. Therefore, we do not expect a linear relationship between ID and speed of movement.

Each subject participated in the experiment for 5 consecutive days. On *days 1* and *5,* both practice and performance testing occurred to determine baseline and improvement with practice. On *days 2*, *3*, and *4*, only practice occurred. Prior to initiating the experiment for each subject, performance was tested on a range of different spoon difficulties. Easy, medium, and difficult spoon sizes were chosen for each subject. The difficult spoon was chosen as the largest ID for which the subject could successfully transport the marble dropping it on fewer than 30% of trials. The medium and easy spoons were the next 1 and 2 spoon difficulties below. Testing was performed on all three spoon sizes as well as the spoon without a marble, but training was performed only on the medium spoon size for each subject.

Table 2. *Details of spoon depths and their computed index of difficulty*

Depth, mm	ID
3	6.33
6	3.16
9	2.11
12	1.58
15	1.26
18	1.05
30	0.63
33	0.57
66	0.28

The inner diameter of each spoon is 19 mm. The index of difficulty (ID) is then computed as the ratio of diameter to depth of each spoon.

Testing on *days 1* and *5* includes two trials of 10 repetitions of forward and backward movements with all three spoon sizes. On each trial, if they dropped the marble more than two times, they had to do the trial again. However, no specific cost was associated with dropping the marble. Training on *days 1* through *5* included 5 sets of 10 repetitions of the same task using only the medium spoon size. In this study, we used the kinematic recordings from the testing on *days 1* and *5*.

Speed-Accuracy Tradeoff (Fitts' Law)

We first tested the effect of ID on speed and determined how this effect changed following practice (1). We fitted a regression line to the movement time (MT) and the index of difficulty (ID) and calculated the index of performance (IP) as the inverse of the MT-ID linear equation slope for each subject. The index of performance (1, 6) is used as a measure to evaluate if their performance improved in *day 5* compared with *day 1*. Statistical analyses were done by lme4 (16), emmeans (17) packages in R-studio (R core team, 2021). A Linear mixed effects model with repeated measures was used to analyze the effect of practice on performance.

We assessed the effect of ID, group (i.e., dystonia or healthy), and testing day (i.e., pre or post), and their interactions as independent variables (fixed effects) on MT and speed of movement (dependent variables) by fitting a linear mixed effect model (16) to the data. In our model, random effects are assumed to be intercepts for subjects and by-subject random slopes for the effect of ID. In the MT model, we assumed uncorrelated slopes and intercepts (*Eq. 1*); however, we assumed correlated slopes and intercepts for the speed of movement linear model due to the singularity of fit (*Eq. 2*).

We then performed an analysis of variance test (ANOVA) and pairwise comparison to obtain the significance of each effect

$$\text{MT} \sim \text{Testing day} \times \text{group} \times \text{ID} + (\text{ID}||\text{subject}) \tag{1}$$

$$\text{Speed of Movement} \sim \text{Testing day} \times \text{group} \times \text{ID} + (\text{ID}|\text{subject}). \tag{2}$$

Marble Kinematic Analysis

If movement speed is limited by the risk of dropping the marble, then speed can be maximized by allowing the marble to move as much as possible within the spoon. We thus analyzed the marble position within the spoon during movement to determine whether maximal areas were used, or whether other considerations such as reduction of risk or physical constraints on movement speed were affecting the performance. The position of the marble inside the spoon lies approximately within an ellipse; thus, an ellipse was fitted to the marble trajectory for each repetition (one forward and one backward movement). This method enabled us to estimate how much of the spoon area is used to achieve the desired accuracy or speed.

The eigenvalues of the movement trajectory (the ellipse diameter along the semi-major and the semi-minor axes) were then computed. We computed a safety margin with the two main eigenvalues, "a" and "b," as a measure to investigate the variability along the first eigenvector of the movement trajectory (e_1), and along the second eigenvector of the movement trajectory (e_2), respectively. This safety margin is computed based on *Eqs. 3* and *4* to determine how sensitive each subject is to the risk of movement, before and after practice. Therefore, a smaller safety margin means that the subject is risk-seeking and therefore they use more of the available variability. Similarly, a larger safety margin means that the subject is risk-averse, and they use less of the available variability (14)

$$e_1 \text{ safety margin } \% = 100 \times \left(1 - \frac{a}{\text{spoon diameter}}\right) \tag{3}$$

$$e_2 \text{ safety margin } \% = 100 \times \left(1 - \frac{b}{\text{spoon diameter}}\right) \tag{4}$$

We explored how these ratios change with respect to speed of movement, ID, and practice, for each subject. We used a repeated-measure analysis with a linear mixed effect model to derive the statistical results of the change in these ratios with respect to the speed and ID with practice. In the mixed effect model, ID, testing day, speed, and their interactions are the fixed effects. Similar to previous models, random effects are the intercepts for subjects and by-subject random slopes for the effect of the index of difficulty (*Eq. 5*). An analysis of variance test (ANOVA) and pairwise comparison were performed to obtain the significance of each effect.

$$\text{safety margin} \sim \text{testing day} \times \text{ID} \times \text{speed} + (\text{ID}\,|\,\text{subject}) \tag{5}$$

Smoothness and Coefficient of Variation Analysis

In addition to analyzing the marble trajectory and movement time, we assessed the effect of practice on change in smoothness and variability. Dimensionless jerk score is a useful measure to investigate movement smoothness which was computed based on *Eq. 6*

$$\text{Jerk score} = \left(\int_{t_1}^{t_2} \dddot{x}(t)^2 \, dt\right) D^5/A^2, \tag{6}$$

in which $D = t_2 - t_1$ is the duration and A is the amplitude of movement (distance) (18). In addition, the coefficient of variation (CV) was derived as the ratio of the speed standard deviation (SD) to its mean for each repetition ($\text{CV}\% = \frac{\text{SD}(v)}{\bar{v}}$) (19).

Similarly, a linear mixed effect model with repeated-measures analysis was used to compare the smoothness and the coefficient of variation (CV) with respect to the groups, ID, testing day, and their interactions.

RESULTS

Speed-Accuracy Tradeoff

We fitted a linear mixed effect model to assess the effect of task difficulty on MT and speed of movement (Fig. 2*A*). The marble trajectory and the fitted ellipse for a patient with dystonia and a healthy subject is shown in Fig. 2*B*. This figure illustrates how they adjust the trajectory with respect to the movement time and index of difficulty.

As illustrated in Fig. 3 and consonant with earlier results on this task (6), the movement speed decreases in all subjects with the increase in task difficulty. Task difficulty is not a limiting factor for the speed of movement as the movement speeds without the marble (ID = 0 in Fig. 3) are faster than the other task difficulties. Within-group comparison of movement speed showed that the subjects with dystonia ($R^2_{\text{ID}} = 0.88$, P value < 0.001) had a significant increase in their speed of movement in all three spoons with practice (*day 1* vs. *day 5*, Fig. 4). There was no significant change in the speed of movement of healthy children with the easier spoon, however, the model predicted an increase in speed with practice in higher task difficulties (medium and difficult) [($R^2_{\text{spoon}} = 0.88$, P value$_{\text{easy}} = 0.48$, P value$_{\text{medium}} = 0.02$, P value$_{\text{difficult}} = 0.04$), ($R^2_{\text{ID}} = 0.77$, P value < 0.05)]. Figure 4 shows the average speed and the standard deviation on *day 1* versus *day 5* for the healthy children and those with acquired dystonia in all three task difficulties. Similar results were obtained by performing ANOVA using type II Wald χ^2 test for dystonia group [$\text{Pr}_{(>\text{chisq})} < 0.001$] and for the healthy group [$\text{Pr}_{(>\text{chisq})} < 0.05$], showing the significant effect of the index of difficulty and the testing day on the speed of movement.

The regression lines of the movement time versus the index of difficulty for *day 1* and *day 5* is shown for in each group in Fig. 5 (only three subjects are shown for clarity). All the regression lines except two patients with acquired dystonia had a slope significantly different from zero (P value < 0.05), meaning the MT changed significantly with the difficulty (they followed the Fitts' law of speed-accuracy tradeoff). The pairwise comparison to estimate the marginal means for the fitted model on the movement time revealed a significant improvement in the index of performance (inverse of the slopes) in healthy group ($R^2_{\text{ID}} = 0.73$, P value $= 0.001$) and the dystonia group ($R^2_{\text{ID}} =$

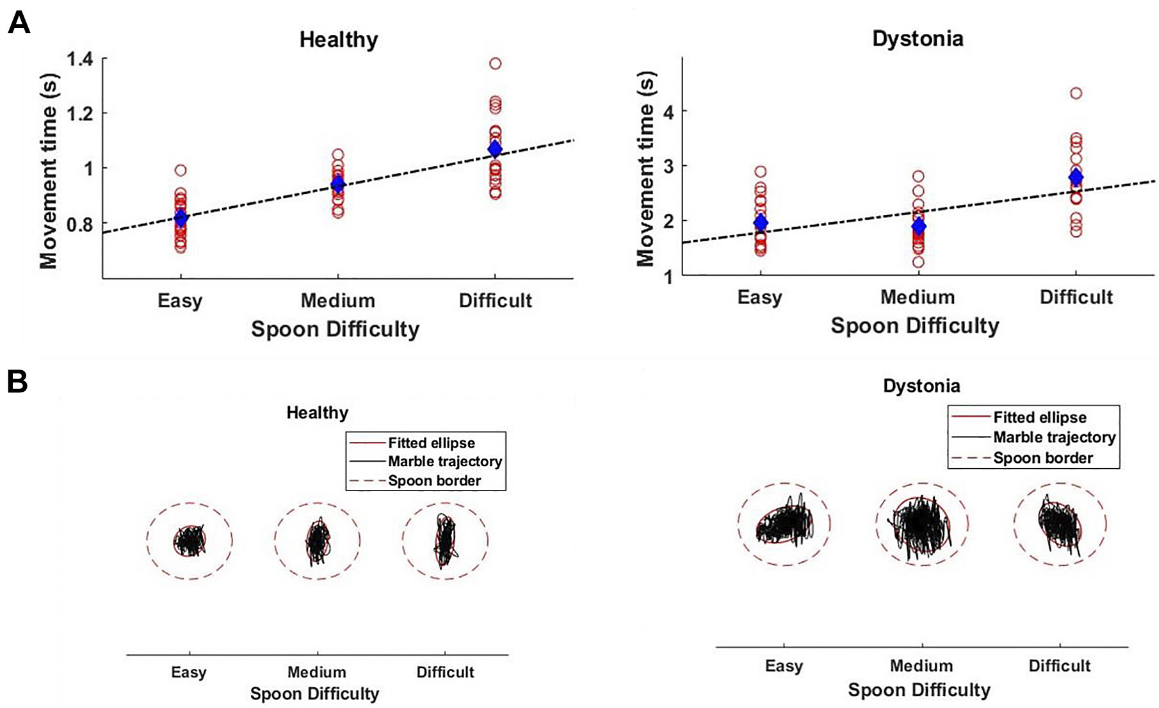

Figure 2. *A*: the movement time with respect to spoon sizes (easy, medium, and difficult) for a subject with dystonia (*right*) and a healthy subject (*left*) is shown with red dots for each repetition. The blue dot shows the average movement time for all repetitions in one trial and the dashed black regression line shows the increasing trend of movement time with respect to the spoon difficulty. *B*: the marble trajectory (black line) within the spoon border (dashed red line) and the fitted ellipse (solid red line) to that trajectory is shown for each spoon difficulty for one healthy subject (*left*) and one subject with dystonia (*right*) in one trial.

0.89, P value < 0.001) with practice (Fig. 6). Analysis of variance (ANOVA) using type II Wald chi-square test performed on the linear models revealed a significant effect [$\Pr_{(>\text{chisq})} < 0.0001$] of testing day and ID but not their interaction (testing day × ID).

Based on the protocol, the spoon sizes that each subject practiced with are consistent throughout the whole experiment from *day 1* to *day 5*; therefore, changes in IP are entirely due to changes in the speed of movement. Movement speed improved significantly for each of the spoon sizes individually in the children with dystonia, but the change in speed for the healthy children was only significant when combining performance across multiple spoon sizes.

Marble Kinematics Analysis

The safety margin in the direction of first eigenvector (e_1 safety margin).

The statistical tests performed on the e_1 safety margin reveal that there was a significant decrease of e_1 safety margin with practice in the healthy control group. The linear model explains 76% of variance in the data ($R^2 = 0.76$) and the ANOVA test revealed that all the variables and their interactions except day × movement speed have a

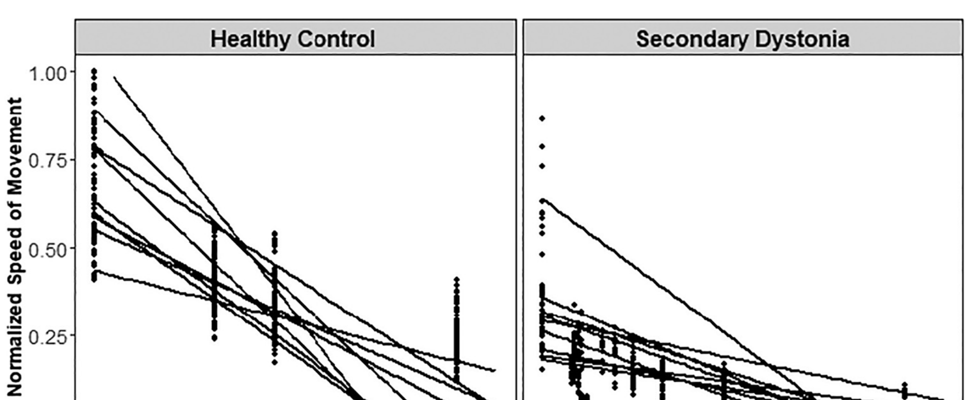

Figure 3. Normalized speed of movement versus the index of difficulty (ID) (higher ID indicates the more difficult task and zero ID indicates the no-marble condition) for the healthy control and dystonia group is shown in dots. Each dot represents the speed for one repetition of task with the corresponding ID, before the training (*day 1*). Regression lines for the speed of movement vs. the ID for each subject (P value < 0.01 for all except two children with dystonia) are shown for both groups. The decreasing trend of movement with respect to the ID indicates that all the subjects follow Fitts' law and adjust their speed based on the task difficulty.

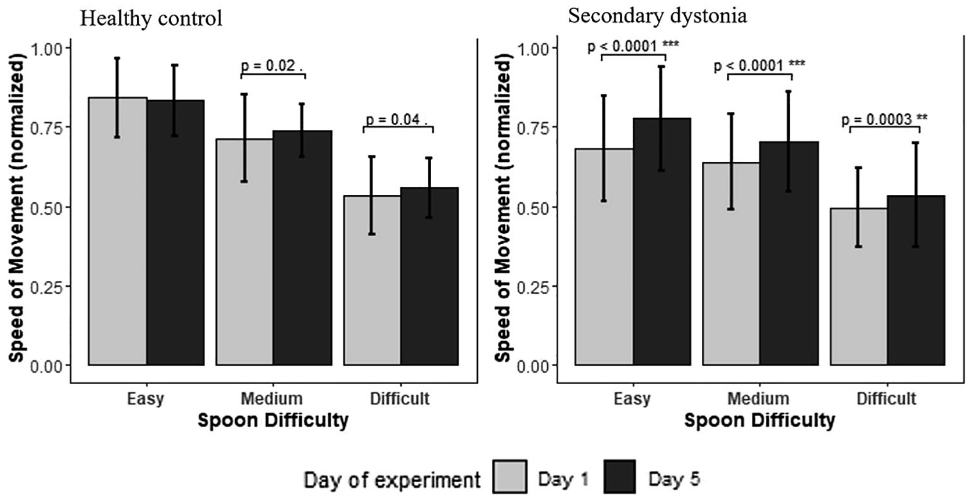

Figure 4. Statistical result of the improvement in the speed of movement in each group with three different task difficulties. The figure depicts the averaged normalized speed of movement and the standard deviation versus the testing day for three spoon sizes in the healthy (*left*) and dystonia (*right*) groups, predicted by the linear mixed effect model.

significant effect on the e_1 safety margin [$Pr_{(>chisq)} < 0.001$].

On the other hand, the effects of these parameters on the e_1 safety margin were shown to be negligible in children with dystonia. The fitted linear mixed effect model ($R^2 = 0.57$) and the performed ANOVA test showed that there is no significant change in e_1 safety margin with practice and with the change of movement speed or ID, in children with dystonia. These results are illustrated in Fig. 7 with respect to spoon difficulty for each group. Figure 8 shows the regression lines for three subjects in each group with respect to ID and speed of movement, respectively.

The safety margin in the direction of second eigenvector (e_2 safety margin).

We fitted linear mixed effect models and performed pairwise comparisons on them for the healthy control group ($R^2 = 0.49$, P value $= 0.50$) and the dystonia group ($R^2 = 0.77$, P value $= 0.43$). The analysis of variance showed only a significant effect of ID × speed [$Pr_{(>chisq)} < 0.0001$] for the healthy control group (Fig. 9). No other significant effects were observed on e_2 safety margin as illustrated in Fig. 9.

Smoothness and Coefficient of Variation Analysis

We performed the same analysis on the jerk scores in both groups. The models explained 79% and 53% or variance of jerk scores in healthy control and the dystonia group, respectively. The analysis of variance showed a significant decrease of jerkiness (increased smoothness) with practice in children with dystonia [$Pr_{(>chisq)} < 0.001$] for the easy task difficulty (Fig. 10*A*). The result is consistent with the pairwise comparison of means that revealed a significant decrease of jerkiness with practice (P value $= 0.01$) in children with acquired dystonia with the easy task (*day 1* mean = 0.4; *day 5* mean = 0.14).

A similar analysis was done on the coefficient of variation of movement in both groups. The models explained 30% and 51% or variance of CV in healthy control and the dystonia group, respectively. The pairwise comparison of mean in group analysis showed there is only a significant change of

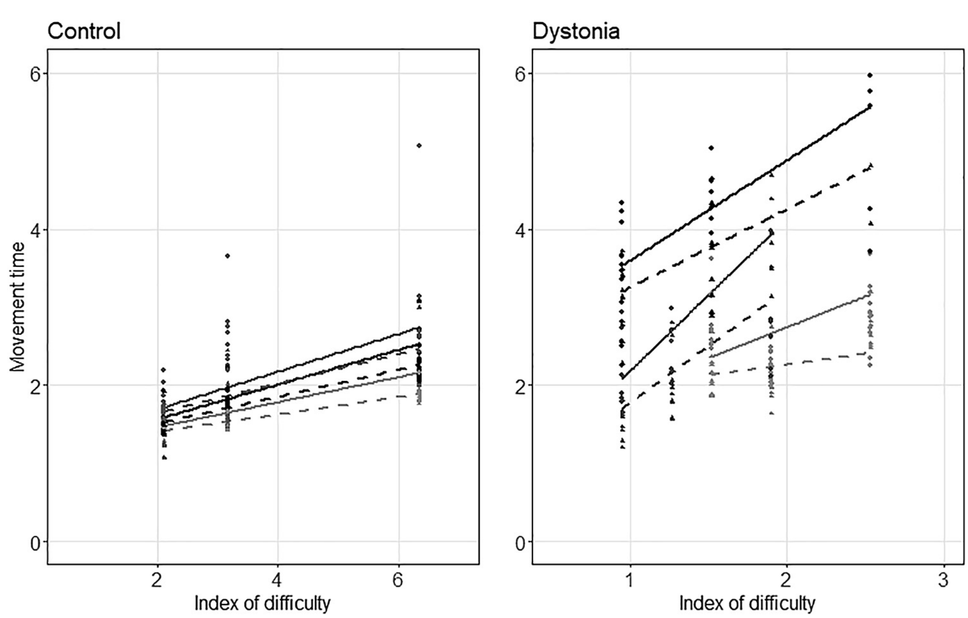

Figure 5. Change in movement time (MT) for three participants in each group (healthy control and dystonia) with respect to the index of difficulty (ID) for *day 1* (solid line) and *day 5* (dashed line). Please note that the ID axis scale is different for healthy children and children with dystonia due to their different capabilities. The slope of each line indicates the inverse of the index of performance for the corresponding subject on either *day 1* (solid line) or *day 5* (dashed line).

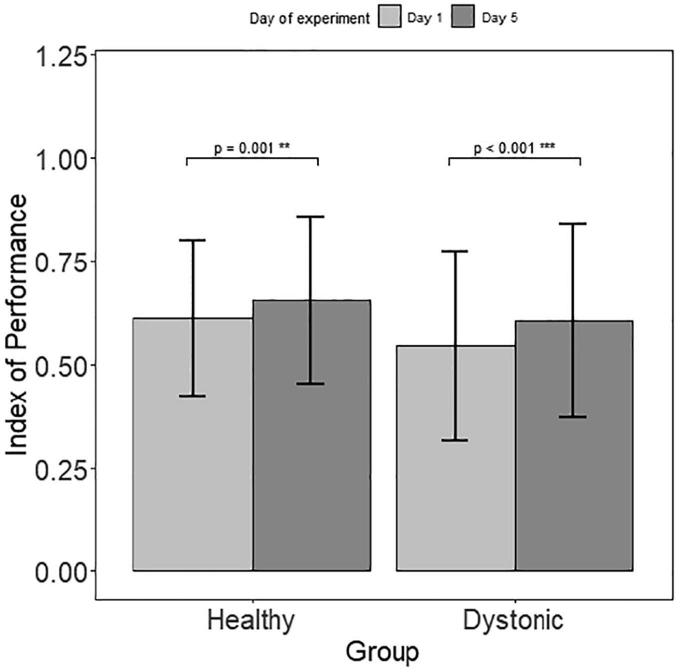

Figure 6. Statistical result of the normalized index of performance (IP) comparison before and after training in each group. An increase in the IP measures the effect of practice on learning.

CV in difficult task (highest ID) in children with dystonia (P value $= 0.003$), however this slope is only significant (P value < 0.05) for six participants of 13 as shown in Fig. 10*B* (*day 1* mean = 56.5, *day 5* mean = 53).

DISCUSSION

In this study, we found that children with acquired dystonia and healthy children were able to improve their performance with practice on a trajectory task constrained only by the risk of dropping the marble. This constraint imposes a limitation on the maximum variability during the task performance, without specifying a particular desired trajectory or endpoint accuracy. It may therefore more closely reflect some aspects of normal movement behavior when tracking or tracing is not the purpose. For example, it may represent some of the challenges faced by children as they attempt to feed themselves with a spoon.

Improvement in performance is reflected in the improvement in the speed-accuracy tradeoff, as measured by increased speed for each level of difficulty, as well as IP. To increase speed without dropping the marble, it is necessary to reduce the movement variability within each trajectory or to decrease the maximum acceleration and jerk of the spoon that would lead to the marble exceeding the bounds of the spoon edge.

We found that smoothness (evaluated by jerk-score) in the lowest task difficulty and speed coefficient of variation in the highest task difficulty improved significantly in children with dystonia but not in healthy children. Although we would have expected a decrease in healthy children, in fact, some of their improvement in performance may have occurred due to a decrease in their initial large e_1 safety margin. In other words, healthy children tended to maintain the marble closer to the center of the spoon, thus perhaps not achieving the maximum speed that could be achieved; therefore, with practice, greater confidence in performance may have allowed them to reduce the safety margin and allow higher levels of variability without exceeding the bounds of the spoon. In contrast, children with dystonia had much less of a safety margin at baseline to begin with, perhaps due to their higher intrinsic variability. The only way that children with dystonia could thus improve performance would be to improve the smoothness and movement variability itself (reflected in either speed coefficient of variation and e_2 safety margin) because the e_1 safety margin could not be safely reduced without dropping the marble.

In conclusion, we have shown that both healthy children and children with acquired dystonia improve skill as measured by the speed-accuracy tradeoff on a trajectory task where variability is constrained by the physics of the task rather

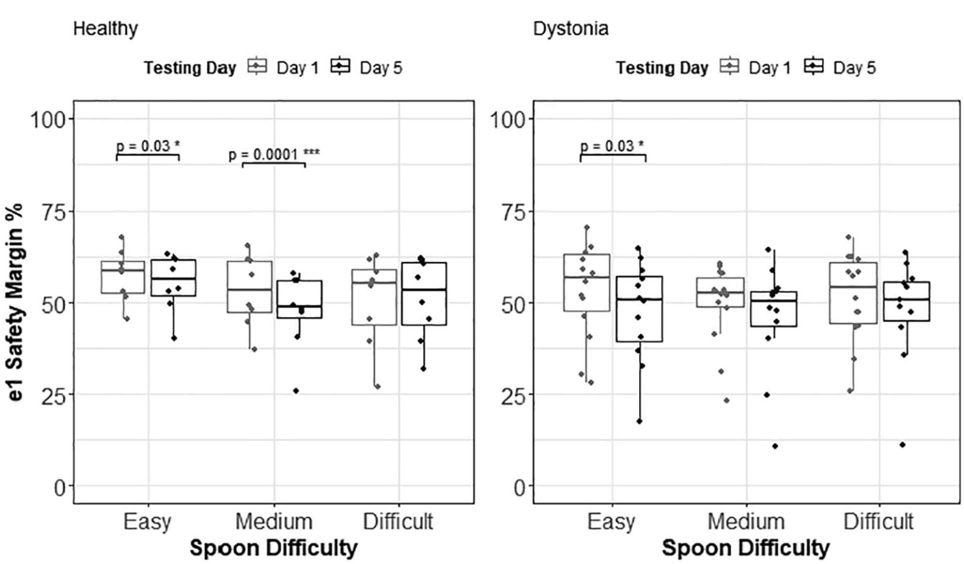

Figure 7. e_1 safety margin group analysis for healthy control group and dystonia group. This ratio does not change with respect to the index of difficulty; however, pairwise comparison revealed that the healthy control group showed a significant decrease in this ratio with practice, performing with easy and medium spoon difficulty; and this ratio only decreased in children with dystonia performing with easy spoon difficulty.

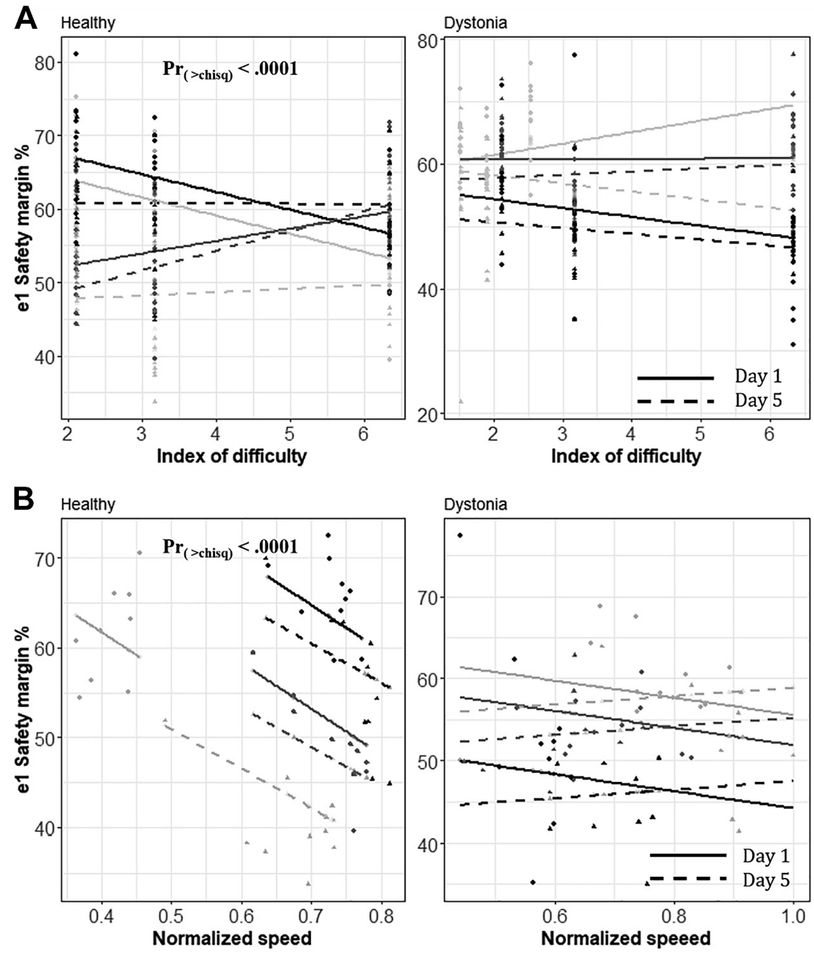

Figure 8. Fitted linear model. *A*: this figure shows the fitted lines for three subjects (three shades of gray) from each group with respect to index of difficulty (ID). The fitted lines are consistent with earlier data shown in Fig. 7; we see a higher decrease in this ratio in smaller indices of difficulty in the healthy control group [$Pr_{(>chisq)} < 0.0001$]. *B*: this figure shows the same fitted lines for those subjects with respect to the speed of movement. It clearly shows that the slopes are significant [$Pr_{(>chisq)} < 0.001$] for the healthy control group, as well as the extent of the drop in this ratio.

than adherence to a target trajectory. Although improvement of performance with practice is not surprising in healthy children, it is nevertheless interesting to note that this is reflected in a change in the speed-accuracy tradeoff, indicating that Fitts' law is not immutable but rather represents the current level of skill and task performance (1, 2, 7). Improvement of performance in children with acquired dystonia is interesting because this suggests that the higher level of signal-dependent noise can be controlled through repetition and learned strategies, and this provides an avenue for the quantitative

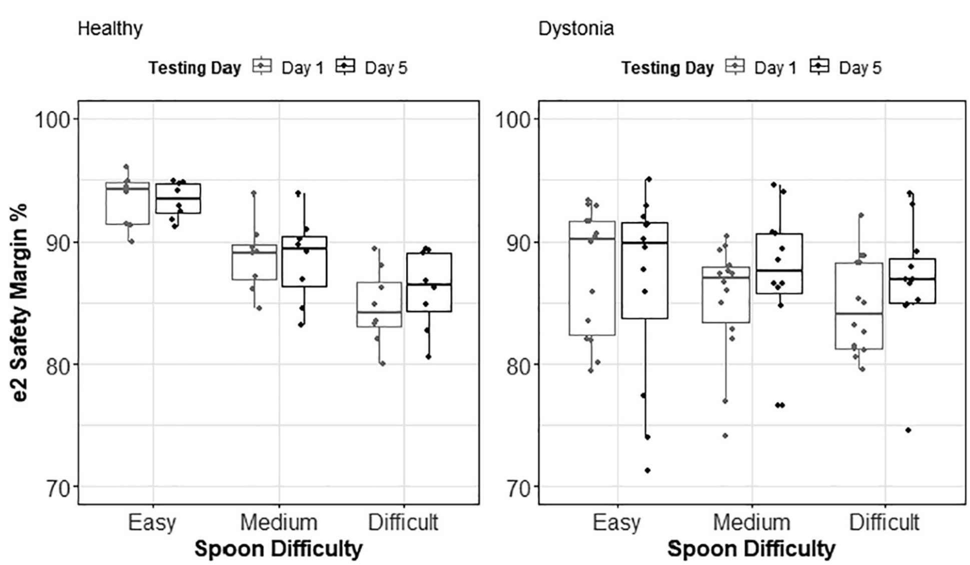

Figure 9. e_2 safety margin group analysis for the healthy control group and dystonia group. There was no change in this measure associated with the practice; however, in the healthy control group there is a significant decay of this measure with respect to spoon difficulty, consistent with the results of ANOVA on the effect of index of difficulty (ID) × speed of movement [$Pr_{(>chisq)} < 0.001$]; The e_2 safety margin decreases as the ID increases in the healthy control group.

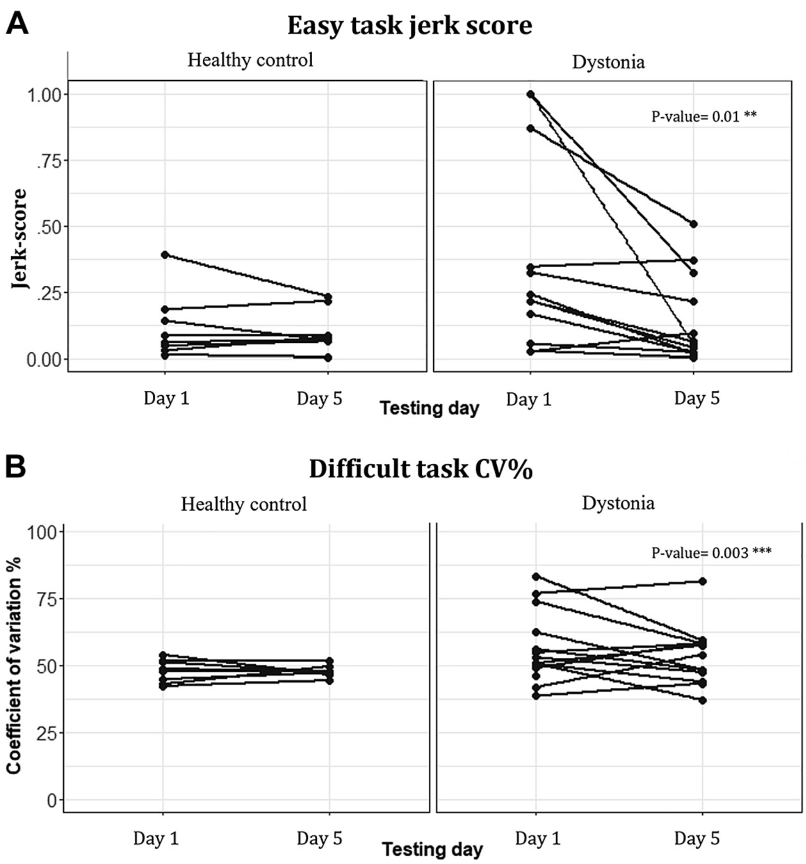

Figure 10. *A*: practicing decreased the lowest task difficulty jerk score in the dystonia group ($P = 0.01$) but the jerk score did not change significantly with practice in healthy children. *B*: practicing decreased the highest task difficulty coefficient of variation (CV) in the dystonia group ($P = 0.03$) but the variability did not change significantly with practice in healthy children.

evaluation of rehabilitation strategies in this otherwise highly challenging group (3–5, 12).

The significant increase in the index of performance arises from different approaches in the two different subject groups. Healthy children improved by reducing the safety margin, and perhaps maintaining the same level of signal-dependent noise, whereas the children with dystonia maintained the same safety margin but reduced their noise and movement variability. Children with dystonia appropriately adjust their speed to compensate for the level of variability, consistent with prior results (2). Prior research has shown that the origins of signal-dependent noise may be different in these two groups, and perhaps only the noise in the children with dystonia is amenable to reduction with practice (2, 5). Further study of modifications of the speed-accuracy tradeoff in this and other tasks are warranted to evaluate the potential for improvement in skill with practice in children with acquired dystonia.

The limitations of this work include the random choice of task difficulties for each subject, however we confirmed that this variable did not have a significant effect on the final results by comparing the outcome variables with respect to both spoon number (task difficulties; easy, medium, and difficult) and ID. In addition, due to the different capabilities of participants, we observed a ceiling effect in the speed of movement in some subjects, however, this was only limited to some repetitions, and the effect was canceled out by fitting linear models.

DATA AVAILABILITY

Data will be made available upon reasonable request.

ACKNOWLEDGMENTS

We acknowledge Ambra Cesareo, Claudia Casellato, Andrea Galbiati, Shinchi Amano, Jonathan Realmuto, and Ritt Givens for support to data acquisition and Aprille Tongol and Elena Beretta for help in patient recruitment.

GRANTS

This work was supported by the US National Institutes of Health Grants R01HD081346-01A and Subaward USC-POLIMI: 61430868 and by the Italian Ministry of Health Grant Ricerca Corrente 2015/2022 (to E. Biffi).

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

E.B., E.A., A.P., and T.D.S. conceived and designed research; M.K., E.B., E.A., A.P., and T.D.S. performed experiments; M.K., E.B., E.A., and A.P. analyzed data; M.K. and T.D.S. interpreted results of experiments; M.K. prepared figures; M.K. drafted manuscript; M.K., E.B., E.A., A.P., and T.D.S. edited and revised manuscript; M.K., E.B., E.A., A.P., and T.D.S. approved final version of manuscript.

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