Effort, performance, and motivation: Insights from robot-assisted training of human golf putting and rat grip strength

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***Abstract*—Robotic devices can modulate success rates and required effort levels during motor training, but it is unclear how this affects performance gains and motivation. Here we present results from training unimpaired humans in a virtual golf-putting task, and training spinal cord injured (SCI) rats in a grip strength task using robotically modulated success rates and effort levels. Robotic assistance in golf practice increased trainees feelings of competence, and, paradoxically, increased their sense effort, even though it had mixed effects on learning. Reducing effort during a grip strength training task led rats with SCI to practice the task more frequently. However, the more frequent practice of these rats did not cause them to exceed the strength gains achieved by rats that exercised less often at higher required effort levels. These results show that increasing success and decreasing effort with robots increases motivation, but has mixed effects on performance gains.**

I. Introduction

Robotic devices that are designed for motor training and rehabilitation can assist their users in achieving desired tasks, such as when they implement assist-as-needed or patient-cooperative training strategies. They can also make tasks more difficult, such as when they implement error augmentation or challenge-as-needed strategies [1], [7], [8]. A complex picture is emerging as to how these strategies affect motor gains. In some cases, these strategies have been found to have no incremental benefit on motor learning or rehabilitation, or even to be detrimental, while in others they seem to aid it [12].

A little-studied aspect of robot-enhanced training is its effect on motivation. Patients sometimes remark that they are motivated by assistance [11], but this increased motivation has not been well quantified. Understanding how human-robot interaction affects motivation is important for understanding the mechanism of performance gains achieved during training, as motivation influences learning [9], [4]. It is also important for understanding how robotic devices might actually be used in the 'real world', in which users are less constrained with respect to how often they must practice with a robotic device compared to laboratory tests that carefully control practice amounts.

Here we report preliminary results from two experiments in which we robotically modulated success rates and effort levels and quantified the effect on motivation and performance gains. In the first experiment we studied how unimpaired trainees responded to error-reducing or error-enhancing force fields in a virtual golf-putting task, using questions from the Intrinsic Motivation Inventory to assess motivation and effort and putt variability to assess performance gains. In the second experiment, we studied how frequently rats with a SCI self-trained their grip function in a robotic strength training task, when the force required by the task was either large or small. We used the number of attempts at the task in a fixed period as a marker of motivation, and quantified performance gains in terms of the strength gained after training.

II. Methods

A. Virtual golf putting training for humans

1) Subjects: Thirty healthy subjects (age 20-30, 8 females, 1 left-handed) with no history of neurologic disorders participated in the experiment. Each participant provided written informed consent in accordance with a protocol approved by the University of California-Irvines Institutional Review Board.

2) Experimental apparatus and robot-generated dynamic environments: Subjects interacted with a three degrees-of-freedom lightweight haptic robot (PHANToM 3.0 Premium, Sensable Technologies, Inc) through a handle. The robot handle attached to the robot arm through a passive $3DOF$ gimbals. Subjects controlled a virtual golf club head by moving the handle with the right hand. Motion of the robot arm was constrained to one dimension (left-right with respect to the subject) via software. The robot was used to apply forces to the subjects hand and record the position and velocity of the hand at a sample rate of $1000Hz$.

The golf game was designed so that the velocity at which the club crossed the starting position during the downswing

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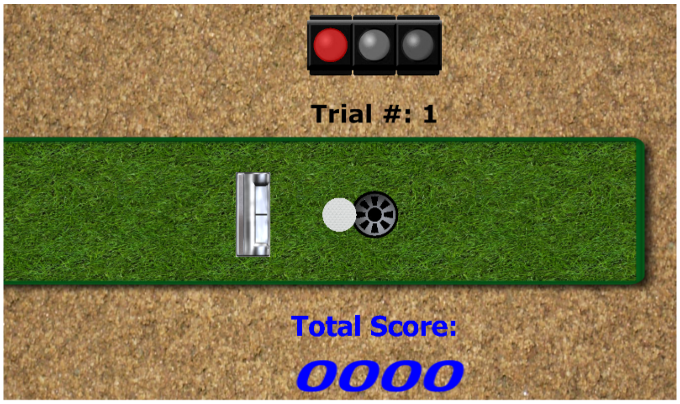

Fig. 1. Graphical interface of the virtual golf game. Participants manipulated the head of a virtual golf putter by means of a $3DOF$ haptic robot. The objective of the game was for participants to hit the virtual golf ball to the center of the hole shown in the screen.The starting position for each swing was the same, however, the distance of the hole was set to either a short or long distance depending on the current phase of the experiment. A total score based on the distance error from the center of the hole and the number of consecutively made putts was also shown during game play.

(defined as the impact velocity) determined the distance traveled by the ball on the screen. Note that compared to actual putting this design removed the effects of variability in the putting surface and variability in the location and angle of the putter face at impact. The goal was to simplify putting dynamics so that impact velocity uniquely determined putt distance.

The robot was programmed to provide dynamic environments in which a subjects impact velocity errors could be haptically reduced or amplified, or used in its backdriveable mode. In the haptic error-reduction training (ER) condition, the robot decreased velocity errors proportional to the predicted error for each putt. In the haptic error-amplification (EA) training condition, the robot increased the velocity errors proportionally to the predicted error. Subjects in the control group (CTRL) experienced no forces from the robot during training. The force field was defined as follows:

$$F_x = \begin{cases} -B_{ER}\dot{x} & \text{error-reduction} \\ B_{EA}\dot{x} & \text{error-amplification} \end{cases} \quad (1)$$

The gains used, B_{ER} and B_{EA}, were constant for all subjects and equal to $3.3Ns/m$ and $3.5Ns/m$ for the short and long targets in the error-reducing condition, respectively, and $1.5Ns/m$ and $1.6Ns/m$ for the error-amplification condition. These gains were chosen after pilot testing with several subjects so that the resulting force field significantly decreased or increased impact velocity errors while being qualitatively unnoticeable to subjects. The goal was to produce a dynamic environment in which subjects did not create a model specific to the haptic robot but rather a model of their arm [5].

The swing for this task can be divided into three main parts: backswing, downswing, and follow-through. Forces were applied only during the downswing by decreasing or increasing velocity errors proportional to the predicted error during the downswing for each putt. The error during downswing was calculated with respect to a target trajectory in the phase space of the swing.

The effect of this algorithm was to define for each putt a target trajectory that began at the actual maximum backswing length of the subject (at which point the head velocity was zero), and then move to the location of the virtual ball with a head velocity equal to the target impact velocity that would cause the ball to move to the center of the selected target (i.e. the short or long target).

3) Experimental protocol: Subjects were instructed on how to perform a putting-like motion (i.e. an appropriate backswing followed by a smooth downswing and follow through) to play the virtual golf game. The objective of the game was to impact the ball so that it would reach the center of one of two target locations: short or long (requiring an impact velocity of $1.12m/s$ and $1.65m/s$ respectively). A trial consisted of first placing the cursor on a predefined starting position a blue rectangle shown on the screen and then performing the putting-like motion. Once the club was held at this position for one second, a golf ball appeared on the screen directly in front of the cursor. The subject then performed the swing to impact the ball.

The experiment was conducted on two separate days for every subject. On Day 1, initial practice day, subjects were asked to perform a total of 100 putts, 50 to each target location. The target locations were randomized prior to the experiment. All subjects were presented with the same randomized order of targets. The purpose of the initial practice day was twofold: (1) familiarize subjects with the task in order to minimize practice effects, and (2) provide an initial putting skill measure that was then used to divide subjects into three training groups with matched average initial performance. This was achieved by ranking the 30 subjects based on their putting performance (defined as their average mean squared error of impact velocity) on Day 1, and then sequentially randomizing the ordered subjects into blocks of three into each training group.

Day 2, training day, was performed 2 to 3 weeks after day 1. It consisted of a total of 170 putts. Although subjects were not told, the 170 trials were divided into three phases: baseline assessment (40 trials), training (90 trials), and short-term retention (40 trials). The target location was randomized for the baseline and short-term retention phases. For the training phase, the same target location was presented in three consecutive trials to allow subjects to adjust their putts based on their performance. This pattern of three putts to the same distance was repeated 30 times during the 90 training trials.

Throughout training, participants were asked questions taken from the Intrinsic Motivation Inventory (IMI). These questions aimed at assessing the participants perceived levels of effort and performance throughout the task [13]. During Day 2, subjects were asked to answer these questions once during baseline (after trial 20), twice during training (after trials 60 and 100), and twice during short-term retention (after trial 140 and trial 170, the end of training). These trials were chosen so as to not interfere with the transitions from baseline to training and training to short-term retention while allowing participants enough time to experience each phase.

4) Data analysis: We were interested in the effects of training in a haptically enhanced environment on the variability of the impact velocity. We therefore quantified performance as the variance in the impact velocity of the virtual golf ball. Previous studies have shown that highly skilled putters are less variable in their impact velocity, even though mean velocities are similar for less and more highly skilled golfers. This variability also increases with target distance [6]. We defined the variability reduction due to training as the ratio of variability at short-term assessment on Day 2 to baseline variability on Day 2. ANOVA tests were conducted between groups on the different training phases with the significance level set to $\alpha = 0.05$. We were also interested in the effects that modulating participants success rates would have on their perceived levels of efforts and competence. This was quantified using questions from the Intrinsic Motivation Inventory. We used a relative scale in which we subtracted each participants response during training and short-term retention from his or her responses at baseline. The Kruskal-Wallis test was conducted between groups for each question with the significance level set at $\alpha = 0.05$.

B. Automatic Grip-Strength (autoGSM) training for rats

1) Subjects: Sixteen Sprague Dawley rats were used for this study. Rats were initially handled for about 3 weeks prior to the beginning of training in order to get them accustomed to human touch. Rats were placed on a food-restricted diet where they received 85% of the normal amount of food in order to motivate them to perform the training task.

2) Experimental apparatus: A robotic grip strength device was designed and implemented in order to measure and train the ability of rats to use their right forepaw in a pulling task. This device, known as the Automatic Grip Strength Meter (auto-GSM), is a 1 DOF robot consisting of a linear actuator and an automatic food dispenser. The rats interact with the robot by means of a metallic bar that holds a food reward on one of its ends. An acrylic glass box was designed to serve as the training ground for the rat as it allows for easy monitoring of the rat behavior with minimal interference on its behavior. The linear actuator serves as a linear spring that the rats must pull towards themselves in order to reach the food reward. When the spring is at rest the food reward sits behind the acrylic box out of reach from the animal. The device simulates a commonly used test to assess grip strength on rats, the Grip Strength Meter (GSM). This experimental setup allows for testing a volitional task where the animal is motivated to pull the bar until the food is within reach. For more details on the GSM and the robotic device see [10].

The autoGSM robot was programmed to work as a linear spring governed by the equation $F = k\Delta x$. Rats interacted with the robot by means of a metallic bar placed at the front of the acrylic box. In its rest state ($\Delta x = 0$), the bar came into the box just enough to allow the rats to hold on to it. On

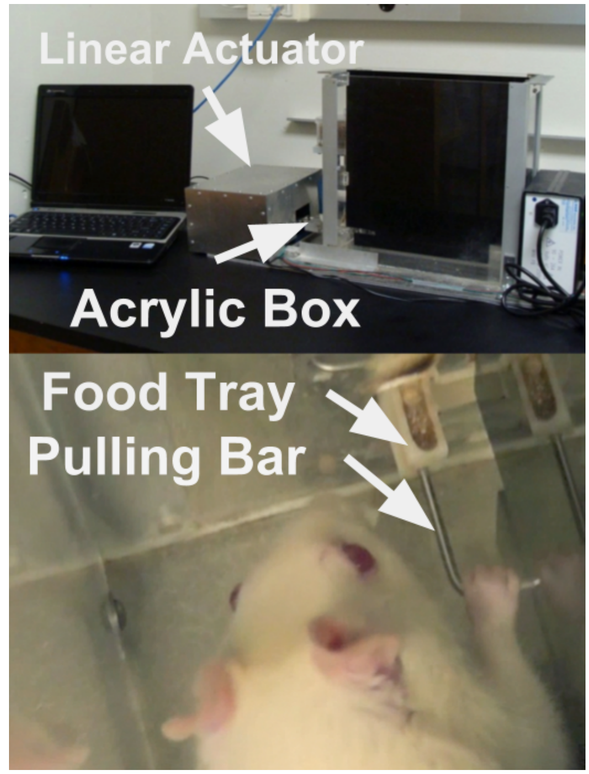

Fig. 2. Robotic training setup for the rats. **[Top]** Computer, linear actuator, food dispenser, and acrylic glass box that comprise the full setup. **[Bottom]** View from the top of the acrylic glass box. This picture shows the required movement from the rat as well as the placement of the food tray on the pulling bar. In its retracted state, the food tray is out of the reach of the rat. The rat is then required to pull the bar to bring the food pellets within reach. Note the geometry of the bar used to ensure that the rat is only able to pull with one paw.

the other end of the bar a food tray was placed that housed chocolate food pellets. The rats were trained to pull the bar with their forelimbs until the food pellet was within reach ($\Delta x = \Delta x_{desired}$). Once the bar was pulled far enough, the linear actuator locked the bar in place to allow the animals enough time to retrieve the food reward. If the rat was unable to pull the bar far enough to reach $\Delta x_{desired}$ the linear actuator snapped back into its resting position. A single trial consisted of the rat approaching the metallic bar, pulling it and either reaching $\Delta x_{desired}$ or not. A successful trial was defined as being able to reach the desired pulling length. Trials where the rat started to pull but was not able to reach the desired pulling length were considered unsuccessful.

Rats were placed into one of two training groups: control or autoGSM. In the control group, the stiffness of the spring was set to be as low as possible. This value was determined to be the minimum force needed for the metallic bar to pull away from the animal if the animal did not pull on it. In the autoGSM group, an adaptive algorithm was used to determine the stiffness of the spring. This algorithm, developed by Spencer [14], increased the stiffness value by a set amount α when a successful pull was achieved and decreased the stiffness value by a value $\delta * \alpha$ when the trial was unsuccessful.

This algorithm seeks to adapt the spring force in order to have the animal pull at its maximum force by the end of each training session.

Rats were surgically intervened to have a unilateral contusion on the fifth cervical vertebra (C5). A contusion of $100kdynes$ was delivered using an Infinite Horizons Impactor (Precision Systems & Instrumentation, Lexington, KY). This type of injury is one of the most clinically relevant models as it simulates a hit to the spinal cord similar to those experienced in car accidents and sporting injuries. Animals were hit ipsilateral to their dominant paw. All surgical procedures were conducted in accordance with IACUC recommendations.

3) Experimental protocol: Rats were trained twice a week according to their training group condition. A training session involved placing the rat in the acrylic box and allowing it to pull 5 times with no resistance in the bar prior to training with any forces from the robotic device. This was done in order to remind the rat that pulling the bar led to a food reward. After these initial 5 trials the spring force was activated and the rat began training. A training session was deemed completed if either the animal reached a total of 30 pulls or if 3 minutes had elapsed. Previous experiments from the group had shown these to be appropriate stopping criteria for healthy animals. Once a week, on a day different than the training days, the rats maximum force was tested. Similarly to the training days, rats were allowed to pull 5 times with no resistance before testing. After these 5 pulls testing begun. Testing was done by increasing the stiffness of the spring to a very high value, one with which the animals could not realistically complete the pull. This allowed us to efficiently assess the rats maximum volitional pulling strength. A testing session was deemed complete after three pulling attempts. The maximum force for a given testing session was defined as the maximum value achieved in the three attempts.

4) Data analysis: We were interested in the effects that modulating the required effort level would have on the rats ability and willingness to pull following injury to the spinal cord. We quantified this by measuring both the number of pulls attempted and the number of successful pulls in a single training session. ANOVA tests were conducted on data from single training sessions at a significance level of $\alpha = 0.05$.

We were also interested in the effects that training with higher force values would have on the rats volitional maximum grip strength following injury. We quantified this during testing days as previously described. ANOVA tests were conducted on data from single testing sessions at a significance level of $\alpha = 0.05$.

III. Results

We studied the effects of robotically modulating participants success rates and required effort levels on their motivation and performance gains. In humans for the virtual golf putting task, we found that decreasing the difficulty of the task by reducing execution errors led to higher feelings of satisfaction and effort, but with mixed effects on actual performance gains. In rats, we found that decreasing the difficulty of the task by reducing the required effort level led the animals to perform the task much more frequently, but this more frequent training did not increase their strength gains.

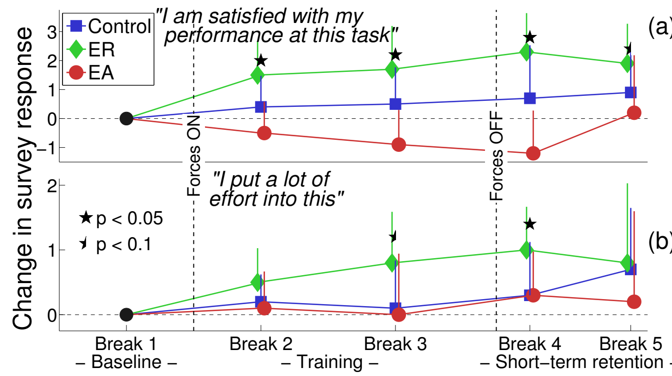

Fig. 3. Response to two of the questions in the Intrinsic Motivation Inventory (IMI) gathered as the golf participants went from training with no forces (baseline), training with forces (training), and finally training with no forces again (short-term retention). **(a)** To the question *'I am satisfied with my performance at this task'* participants in the error-reduction (ER) group show a significantly higher level of self-efficacy compared to those who trained with no robotic intervention (Control) or error-amplifying (EA) forces both during training as well as after training where their performance is not as good. **(b)** To the question *'I put a lot of effort into this'* participants in the ER group present higher levels of perceived effort even though during training the robot was significantly lowering the level of difficulty of the task.

A. Human virtual golf putting

We compared how the responses of participants to specific questions from the Intrinsic Motivation Inventory changed as they went through the different phases of game play: baseline, training, and short-term retention (Fig 3). We asked participants to rate, on a scale from 1 to 7, with 7 being the highest, the statement: *'I am satisfied with my performance at this task'*. Relative to their baseline responses, participants feeling of satisfaction were significantly different once the force field was turned on (Break 2: Kruskal-Wallis, $\chi^2 = 11.1$, $p = 0.004$) and through training (Break 3: Kruskal-Wallis, $\chi^2(2, 27) = 11.9$, $p = 0.003$) and the beginning of short-term retention (Break 4: Kruskal-Wallis, $\chi^2(2, 27) = 15$, $p < 0.001$). At the end of the short-term retention phase the difference was close to being significant (Break 5: Kruskal-Wallis, $\chi^2(2, 27) = 5.2$, $p = 0.076$). Those in the error-reduction group showed the highest levels of satisfaction with their performance while those in the error-amplification group showed the lowest. Additionally, we asked participants to assess their perceived level of effort by scoring, from 1 to 7, with 7 being the highest, the statement: *'I put a lot of effort into this'*. Relative to their baseline scores, participants perceived levels of effort were close to being significantly different towards the end of training (Break 3: Kruskal-Wallis, $\chi^2(2, 27) = 5.1$, $p = 0.08$) and they become significantly different at the beginning of the short-term retention phase (Break 4: Kruskal-Wallis, $\chi^2(2, 27) = 5.7$, $p = 0.05$). Those in the error-reduction group consistently showed higher perceived levels of effort than the other two groups.

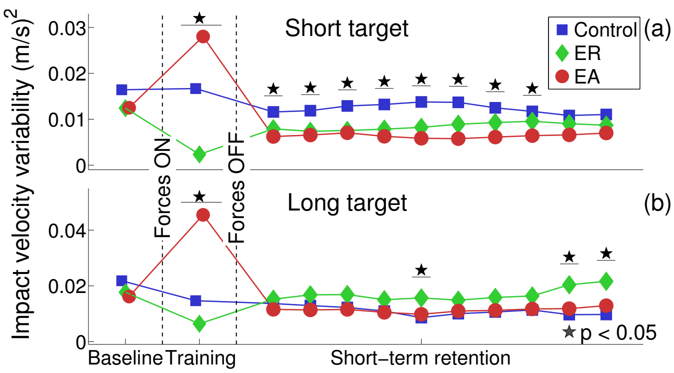

Fig. 4. Variability in impact velocity in the virtual golf task. This figure shows the average variability of the last 10 trials at baseline, the average variability across all trials during training, and a moving average of the variability during short-term retention. During baseline the three groups performed at similar levels. Once the robotic forces were turned on, those in the EA group experienced haptically-increased errors which led to significantly higher variability for both target locations. Those in the ER group experienced haptically-reduced errors which led to significantly lower variability for both target locations. Those in the control group show improvements due to regular training. Following the removal of the force field, those in the EA and ER groups performed significantly better than the Control group at the short target **(a)**, but this difference was gone by the end of the short-term retention. For the long target **(b)** all three groups initially performed at comparable levels once the force field was removed. However, those in the ER group tended to perform slightly worse with the difference becoming significant towards the end of the short-term retention assessment.

During training, variability in the impact velocity was significantly different between training groups for both the short (Fig 4, ANOVA, $F(2, 27) = 30.1$, $p < 0.001$), and long (ANOVA, $F(2, 27) = 46.7$, $p < 0.001$) target locations, confirming that the robotic force fields either substantially decreased or increased putting errors depending on the type of force field experienced. To assess performance gains in the putting game, we compared participants impact velocity variability following training in the force fields, using a 10-sample moving average of the variance in order to gain a better understanding of the temporal patterns of the variability across training groups. For the short target, subjects in the error-reduction and error-amplification groups performed significantly better (ANOVA, $p < 0.05$) than the control group during the beginning and middle portion of the short-term retention phase. For the long target, all groups performed at the same level during the beginning and middle portion of the short-term retention phase with some differentiation apparent towards the end of the assessment when the error-reduction group performed worse than the other groups.

B. Rat grip-strength training

We compared rats willingness to pull the bar before spinal cord injury, following SCI and before and after separating them into two training groups one that trained at higher levels of force (the autoGSM group), and one at lower levels of force (the control group). Willingness to pull was measured as the number of pulls in a one minute test period. Prior to being divided into the control and autoGSM groups both groups pulled at comparable frequencies and with similar success

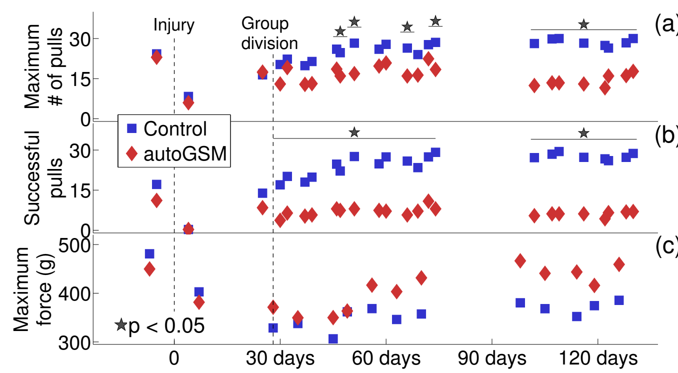

Fig. 5. Pulling and maximum forces data for the rats. The rats had been trained on the pulling task for more than 70 days prior to the injury. After the injury the number of pulls tried was significantly lower **(a)** and the number of successful pulls goes to zero for all animals. The rats where trained for a few weeks until pulling became somewhat consistent again. At this time, they were separated into two groups: Control and autoGSM. Animals in the Control group trained at substantially lower force levels than those in the autoGSM group. Once the animals were separated, those in the Control group where willing to pull more often **(a)** and achieved significantly higher success at pulling **(b)** than those in the autoGSM. However, even after many weeks of training at different force levels, the maximum force generated by the two groups **(c)** was not significantly different in a single testing day.

(Fig 5). Following injury, both groups significantly decreased by a comparable amount in their willingness to pull the bar. Once the rats were divided into the two training groups, those allowed to pull with lower forces (the control group) had a significantly higher number of pulls and successful pulls than those training with higher forces (autoGSM) (Fig 5) (ANOVA, $p < 0.05$). Regarding the strength training of the rats forelimbs, the group that trained with the higher forces consistently showed higher maximum force output, but these differences were not significant for any particular day of testing (Fig 5c).

IV. Discussion

For the virtual golf task, we used a robotic device to either substantially reduce or increase putting errors. There was a clear effect of these robotic interventions on the subjects satisfaction with their performance: robotically decreasing putting errors improved satisfaction, while robotically increasing putting errors decreased satisfaction. Paradoxically, subjects who experienced robotically increased success also reported an increased sense of effort at the task. In terms of actual performance gains, training with error reduction marginally improved short-term retention for short putts, but degraded it for long putts, even though trainees were more satisfied with their performance. Training with error augmentation produced better performance for both short and long putts, even though trainees were less satisfied with their performance.

For the rat grip strength training task, injury of the spinal cord dramatically decreased the rats motivation to perform the task. Rats who were then permitted to train at the task with lower forces performed the task significantly more frequently, compared to rats who were required to pull forces near their maximum capability. Their increased frequency of training was not enough, however, to overtake the performance gains achieved by the rats pulling with more force but fewer times. A recent study by van der Brand et al. [2] showed that a training paradigm that encouraged rat participation (high motivation) triggered higher levels of plasticity and recovery of voluntary control compared to automated training (low motivation) for locomotion in rats with a spinal cord injury.

These were disparate experiments, but they produced compatible results, suggesting they may relate to a general principle of robot-assisted motor training. Enhancing motor performance with robots by using them to decrease task errors (as in the golf task) or to decrease the effort required to do the task (as in the grip training task) can increase motivation. On the other hand, practicing with robot assistance has variable effects on the performance gains experienced with training. Robots may thus serve a key role in motivating practice in the real world, although care must be given so that they do not impair performance gains.

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