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Haptically Assisted Golf Putting Through a Planar Four-Cable System

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Abstract

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ABSTRACT

Individuals learning a new sport often repeat a motion hundreds or thousands of times to try to perfect their form. The quintessential example of this process may be a beginning golfer struggling to learn to putt, where strokes must be precise and consistent in order to place the ball in the hole. This paper presents a four-cable haptic device designed to help golfers learn to improve their putting accuracy. This planar three-DOF system provides feedback that consists of two Cartesian forces and one angular moment. We present the system's design and kinematics, along with a closed-loop controller that helps the user keep the putter head at the correct angle in the plane. We evaluated our design through a study in which five subjects used the system to repeatedly putt at a target both with and without assistance. While assistance did not change the mean of the putting distribution, it did significantly affect the variance for some subjects.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1 INTRODUCTION

Succeeding at golf requires excellent form. Rather than attacking the ball with pure strength, one must swing the club with precision and consistency. The golfer's goal is to use as few strokes as possible to hit the ball into a 10.8 cm diameter hole hundreds of meters away from the starting tee. Several different golf swings and clubs are used for specific parts of the game, for example driving the ball off the tee with a driver or wood, hitting with an iron on the fairway, and putting on the green with a putter. A golfer will take several strokes to get the ball from the tee, through the fairway, and onto the green, with putts accounting for approximately 40% of the strokes taken during a round.

Putting is an important but difficult golf skill; it requires great precision to make the ball roll into the hole from even just two or three meters away. There is little tolerance for angular error of the putter head because small changes have a significant effect on the trajectory of the ball. The golfer must also make sure to hit the ball hard enough to reach the hole, but not too hard to bounce out. The external factors of wind, weather, distractions, and the speed and slope of the green elevate the difficulty of putting to the point where even lifelong golfers are always striving to improve. Despite the difficulty of playing well, golf is a very popular sport that boasts 22.3 million players in the United States [1] and tens of millions more worldwide.

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Figure 1: The planar four-cable haptic putting system. Though difficult to see, the cables extend from the edges of the putter head to the motors located in the four corners of the rectangular metal frame.

Golfers spend considerable time practicing on the driving range and on the putting green to try to master the sport. They may conduct this practice individually, with a golf instructor, and/or with a training aid. Because so much emphasis is placed on learning the correct swing for each club, golf swing trainers are used by many beginning golfers who want extra help to supplement their lessons and by many who are trying to learn golf on their own. The United States market for golf equipment alone was 5.8 billion US dollars in 2005, with the submarket that includes golf trainers accounting for 445.46 million US dollars [8]. The size of the growing market for golf trainers shows that there is great interest in developing new technologies to help individuals quickly learn the proper method of swinging a golf club.

Haptic interfaces are mechatronic systems that enable programmable physical interactions between a human user and a real, remote, or virtual environment. Often taking the form of small desktop devices built like lightweight robot arms, impedance-type haptic interfaces measure the user's motion (position, velocity, orientation, and angular velocity) and respond with forces and torques that seek to guide them to a desired configuration. Given the difficulty of hitting a golf ball correctly, we are intrigued by the idea of using haptic feedback to help novices learn to golf. Though there exist many commercial haptic interfaces, none is well suited to this task, so we set out to design a custom system for this purpose.

Section 2 reviews several key examples of existing golf training devices and discusses large-workspace haptic systems designed for other areas of sports training. Given their successful use in similar applications, we chose to build a cable-based haptic interface for golf putting, as described in Section 3 and pictured in Fig. 1. Section 4 describes the kinematic calculations and control algorithms used to actuate our cable-driven haptic interface. Section 5 presents the results of a user study conducted to determine whether the assistance currently provided by the system affects the user's putting performance. We summarize our work on this golf putting trainer and suggest future research in Section 6.

2 Background

Both passive and active haptic interfaces have been used in various ways as golf training mechanisms. Kopher invented a collapsible wrist support that gives a golfer tactile cues to keep the wrist aligned with the back of the forearm during a golf swing [6]. The device holds the wrist in place until the user exerts enough pressure (by flexing in the wrong direction) to collapse the support, providing a salient error cue. The downside to an invention like this one is that the user doesn't know exactly what they did wrong. Other haptic golf trainers include the commercialized GyroSwing, made by SKLZ [9]. The GyroSwing has a 20,000 rpm gyroscope located in the club head that guides the club to the correct swing plane. If the golfer deviates away from the desired trajectory, the gyroscope resists the movement, providing a torque on the club until the correct plane is found again. Although this club gives constant feedback, adding a gyroscope increases the mass of the club head, and the vibrations from the gyroscope may interfere with the user's experience. Linkage mechanisms have also been used to assist the swing during training. Hart developed a versatile sports swing trainer that used a physical mechanism consisting of a spring, a flexible rod, and a linkage to guide a golf swing [3]. The downside of a device like Hart's is that the linkages add significant inertia to the club so that the user will never achieve the feel of swinging in free space.

Alternatively, cable-driven kinesthetic haptic devices (also called wire robots) have the potential to solve many of these problems. Cable systems are frequently used in sports simulation as well as in general force-feedback haptic devices because they are lightweight and can have a large workspace. Although no papers were found that relate to golf training, cables-driven systems are used in various other sports applications, as described below.

In one example, von Zitzewitz et al. developed a cable-driven rowing simulator to mimic the feeling of rowing in water [12, 11]. The forces the rower should feel at each point in the stroke were recreated using an actuated cable attached to the oar. This work differs from our project's goal because it focuses on using haptic technology to simulate a real physical interaction, while we are interested in using haptics to help the user learn a certain movement. Nonetheless, it was useful to see the design of this rowing simulator's actuation unit, which consists of a motor, a safety brake, and a winch.

In another example, Kawamura et al. developed a system to provide haptic feedback during a tennis swing [5]. Their device aims to apply appropriate reaction forces to the user as they hit a virtual tennis ball. The authors use a seven-cable system and present a method for calculating the wire tensions in real time to apply the necessary forces and torques on the grip while the ball is being hit. Although they again had a different focus of use for their cable system, the fundamental method of calculating cable tensions in real time was useful to our work.

Other literature discusses in detail the design and actuation of force-feedback cable systems. In particular, Shank's master's thesis evaluates an existing planar three-cable haptic interface, including motor selection, motor mounts, capstan radius selection, and cable management [10]. The thesis also contains MATLAB code for simulating the three-cable haptic interface along with code for computing the forward and inverse kinematics based on cable lengths and the cable tensioning algorithm. This paper was a useful reference for our current project because it enabled us to avoid making the same mistakes that Shank experienced with his first design.

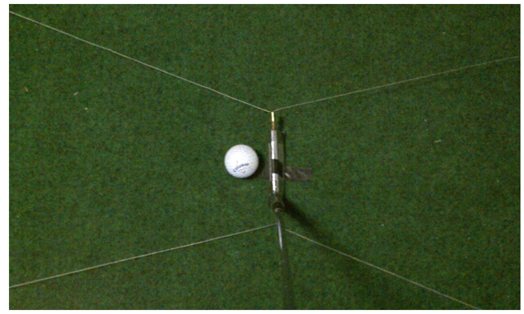

Figure 2: Overhead view of the putter with the four cables and a golf ball. Each cable is securely crimped into a threaded brass cable terminator that is screwed into a threaded hole in the putter.

Lastly, Yang and Zhang developed a planar three-DOF cable-driven force-feedback device for use in virtual applications such as video games [14]. Though the applications are distinct, our four-cable planar system is very similar to the system they built, especially the forward and inverse kinematics. While Yang and Zhang were primarily interested in calculating the maximum force and torque their device could output at various positions, we are focused on using such a system for the practical application of teaching users how to putt a golf ball correctly.

3 System Design

The success of the aforementioned haptic interfaces led us to create a cable-driven device for teaching golf putting. Many novice golfers find it difficult to consistently strike the ball at the optimal location. Hence, we elected to add haptic feedback to a real putter during a real putt rather than attempting to create an appropriate virtual environment. Adopting this haptic augmented reality approach [4] allows us to make the interaction as similar to real golf putting as possible, and it frees us from the tasks of providing graphical, auditory, and haptic feedback of virtual ball impacts. Instead, we concentrate our efforts on methods for delivering haptic feedback that can help the user improve their putting performance.

Providing full six-DOF haptic feedback with a cable-driven haptic interface requires at least six cables. Such designs are typically implemented with eight cables running from the interface object to motors mounted in the corners of a rectangular frame or room, as done in [13], so that all of the cables can stay in tension at all times. While a putter head can freely translate and rotate in three dimensions, a proper putting motion does not typically require the golf club to travel more than a small distance in the vertical direction. We thus assume that the desired putting movement is nearly planar, so we created a planar haptic feedback system with four actuated cables located in a horizontal plane coincident with the plane of the desired putting motion. This three-DOF system tracks the two Cartesian coordinates of the center of the putter head plus the angle of the putter head in the plane. If the motors always act to keep the cables tensioned, the cable lengths can be used to calculate the current pose of the putter head. Varying the cable tensions produces a net force in the plane and a net torque around the axis perpendicular to the plane. Though attractive for its simplicity, this planar design has the potential shortcoming that deviations from the device's plane cause a net force back toward the target plane. The subsections below describe the hardware and software we created to realize the envisioned system.

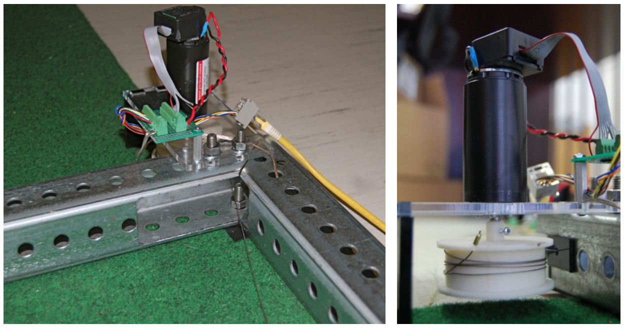

Figure 3: Left: A corner of the frame showing the cable exit. Right: The motor, encoder, and capstan configuration. The cable stays tight around the capstan and does not tangle.

3.1 Hardware

The core interface element in our system is a right-handed iron golf putter, as shown in Fig. 2. It has a flat club face that is used to hit the ball to the golfer's left. We modified the front and back ends of the putter's head to include attachment points for the four cables. Two holes were drilled and tapped on the front end of the putter, and two holes were drilled and tapped at the back end of the putter, with each pair of holes in a vertical line. The four cables were constructed of highly flexible 0.61-mm-diameter stainless steel wire rope. The end of the cable that meets the putter was attached to a threaded brass cable terminator via crimping. Each terminator screws into a threaded hole to firmly attach its cable to the putter head. Because the vertical separation of the insertion points creates a moment about the axis that runs along the putter head, we kept this distance as small as possible at 0.8 cm.

The frame of the golf trainer is a 71 cm × 152 cm rectangle made of 5 cm × 5 cm square perforated steel with 0.9 cm holes, as shown in Figs. 1 and 3. Aluminum brackets screw onto the corners of the frame to hold it together. The frame was slightly lifted off the ground to place the cables in the plane of the desired putting movement. Each cable connects to a DC motor mounted to a corner of the frame. The motor mounts are cut from sheet acrylic plastic, and they attach to the frame with two screws each. Approximately 10 cm of material was removed from the inside end wall of each frame piece to make room for the cables to move freely.

A 5.46-cm-diameter capstan is affixed to the shaft of each motor using a setscrew. The capstans were custom designed and 3D-printed in ABS plastic. Each cable was threaded through a small hole in the capstan's base and then crimped into a brass cable terminator. When the putter is at its starting position in the center of the rectangular frame, each capstan is half wound with cable, which allows the putter to travel forward and backward, reaching the entire workspace without running out of cable.

The system uses four Maxon DC motors to enable smooth movement of the putter head. We selected model #118800, a 36 mm diameter non-geared DC motor with graphite brushes that delivers up to 0.0779 N·m continuous torque. Its maximum continuous current is 1.45 A, and its torque constant is 0.0566 N·m/A. Each motor is driven by a custom linear current amplifier circuit built around the OPA544T chip with a gain of 1 A/V. As seen in Fig. 1, the amplifiers are powered by a pair of bench-top adjustable power supplies set at ±15 V, each of which can deliver a maximum current of 3 A. The input to each linear current amplifier is an analog voltage created by the computer via a Sensoray 626 PCI card.

Attached to each motor shaft is a HEDL 5540 incremental optical encoder, which has a resolution of 500 counts per revolution before quadrature. The encoder signals are read using four quadrature encoder inputs on the Sensoray 626 card. These readings enable the system to calculate the pose of the golf club at any instant, as discussed in Section 4.1. The resulting nominal resolution of the system's cable length measurements is about 86 μm/tick.

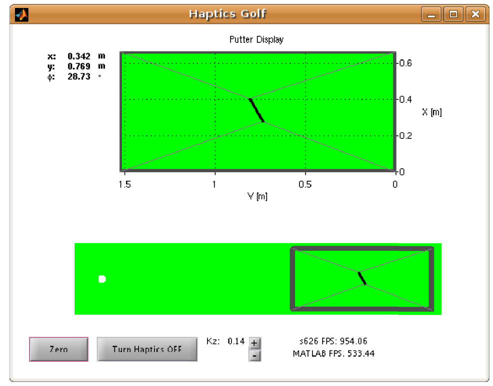

Figure 4: The Matlab GUI displays the position and orientation of the putter head in real time. The display also allows the user to calibrate the system and make simple adjustments to the controller.

3.2 Software

All of the golf putting system's software was developed in MATLAB to allow for rapid development and testing. Our architecture includes a MEX (MATLAB Executable) interface to the Sensoray 626 PCI card mentioned previously. This MEX file creates a haptic feedback thread that runs at 1000 Hz. This fast thread handles all of the low-level processing in the system, which includes reading the encoders, converting the encoder counts to cable lengths, and outputting analog voltages to the linear current amplifiers to create the necessary torque in each motor. All of this information is available in real time inside of MATLAB. We set up a slower loop, running between 200 and 300 Hz, to do the higher level processing. This loop calculates the putter's current pose from the most recent cable length readings and computes the appropriate haptic feedback to apply given the chosen controller and gains.

We took advantage of MATLAB's plotting and graphing capabilities to create a graphical user interface (GUI) for the system. As shown in Fig. 4, it displays the putter position and orientation in real time. The GUI also lets the user enable or disable the haptic feedback and change the haptic feedback gains while the system is running, which allows the user to easily test and compare different configurations.

4 Kinematics and Control

After assembling the physical hardware of the system and implementing the low level software interface in MATLAB, we analyzed the putter's kinematics, calculated the Jacobian, and designed a sample controller that might help a user learn to putt correctly.

4.1 Input Processing and Forward Kinematics

During operation, finding the pose of the putter requires an analysis of the four measured cable lengths, as was done for a similar system in [14]. When our system is first turned on, all of the motors are driven with a small constant current to tension the cables. The user places the putter head in the nominal configuration at the center of the frame, as marked with black tape visible in Fig. 2, and the cable lengths are initialized at their known values. Fig. 5 shows an overhead diagram of the rectangular frame, the four wires, and the putter head. We define the coordinates of the center of the putter as x and y, and the angle the putter makes with the x-axis is ϕ. The cable attachments at the back end of the putter are located at (x_1, y_1), and attachments at the putter tip are at (x_2, y_2). The frame's

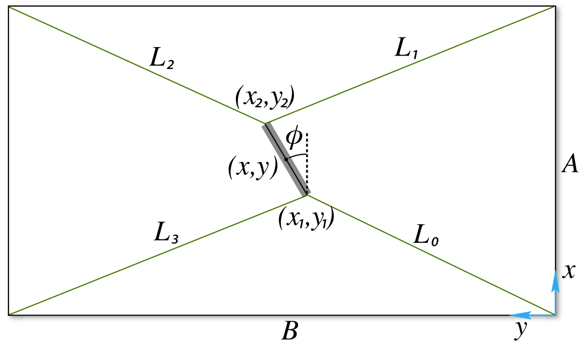

Figure 5: Diagram used to derive the kinematic equations. Note that the coordinate frame is rotated 90° counter-clockwise from the standard x-y view to present the workspace from the user's perspective.

internal dimensions are $A = 61$ cm and $B = 142$ cm. We begin by formulating the inverse kinematics, which provide expressions for the length of each cable (L_0, L_1, L_2, and L_3) as a function of the cable attachment locations and the frame size:

$$L_0 = \sqrt{x_1^2 + y_1^2} \tag{1}$$

$$L_1 = \sqrt{(A - x_2)^2 + y_1^2} \tag{2}$$

$$L_2 = \sqrt{(A - x_2)^2 + (B - y_2)^2} \tag{3}$$

$$L_3 = \sqrt{x_1^2 + (B - y_2)^2} \tag{4}$$

When running, our system measures these cable lengths and needs to calculate the pose of the putter head. Solving these equations for the coordinates of the cable attachment points yields:

$$x_1 = \frac{\sqrt{-B^4 + 2B^2L_0^2 + 2B^2L_3^2 - L_0^4 + 2L_0^2L_3^2 - L_3^4}}{2B} \tag{5}$$

$$x_2 = -\frac{\sqrt{-B^4 + 2B^2L_1^2 + 2B^2L_2^2 - L_1^4 + 2L_1^2L_2^2 - L_2^4} - 2AB}{2B} \tag{6}$$

$$y_1 = \frac{B^2 + L_0^2 - L_3^2}{2B} \tag{7}$$

$$y_2 = \frac{B^2 + L_1^2 - L_2^2}{2B} \tag{8}$$

One can calculate x, y, and ϕ from these values as follows:

$$x = \frac{x_1 + x_2}{2} \tag{9}$$

$$y = \frac{y_1 + y_2}{2} \tag{10}$$

$$\phi = \text{atan2}(y_2 - y_1,\ x_2 - x_1) \tag{11}$$

4.2 Jacobian and Output Processing

As is commonly done for impedance-type haptic interfaces [2], we use the transpose of our device's Jacobian to output haptic feedback through the four motors. Given the desired planar force and moment outputs (F_x, F_y, and M), we calculate a vector of the four forces that the cables need to exert, as follows:

$$\begin{bmatrix} F_0 \\ F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} \partial x/\partial L_0 & \partial x/\partial L_1 & \partial x/\partial L_2 & \partial x/\partial L_3 \\ \partial y/\partial L_0 & \partial y/\partial L_1 & \partial y/\partial L_2 & \partial y/\partial L_3 \\ \partial \phi/\partial L_0 & \partial \phi/\partial L_1 & \partial \phi/\partial L_2 & \partial \phi/\partial L_3 \end{bmatrix}^T \begin{bmatrix} F_x \\ F_y \\ M \end{bmatrix} \tag{12}$$

At each time step, the software evaluates the three-by-four Jacobian matrix for the current putter configuration, takes the transpose, and left-multiplies it into a column vector of the desired outputs.

We convert the cable tensions to motor torques using the capstan radius. The appropriate voltage command is then calculated using the motor torque constant and the linear current amplifier gain. Note that this Jacobian transpose approach does not explicitly take into account the fact that cables can only pull, not push. This approach is sufficient for our present control algorithm, as described below, but it would need to be updated to accomplish more complex haptic output functions.

4.3 Closed-Loop Control

The described system could be used to implement a variety of haptic output algorithms, many of which might have the potential to help the user learn to putt. One likely formulation would be to define a desired club pose, take the difference between the actual and desired poses, and apply forces and torques to guide the user toward the target pose. Another promising alternative would be to use the cables to disturb the motion of the putter, so that the user needed to focus even more on controlling it to the desired pose, as recently done for an arm motion task by Lee and Choi [7]. For an initial demonstration, we chose to implement guidance on putter head angle, ϕ, because this aspect of club pose seems to have the most significant effect on the trajectory of the ball. Consequently, we set F_x and F_y to zero and focus on M, the net moment on the club head. In a correct putt, the club head stays perpendicular to the line between the ball and the target, so we set $\phi_{des} = 0°$. We then make the output moment proportional to the club angle error, as defined below:

$$M = k_z(\phi_{des} - \phi_{actual}) \tag{13}$$

Here, k_z is the controller's torsional stiffness in Nm/°.

Because the system's kinematic calculations are not valid when the cables are slack, we set the minimum motor current to 0.3 A, which corresponds to a cable tension of 0.62 N. One can then see how a problem may arise when we apply the Jacobian transpose in coordination with our feedback control. More specifically, the motor torques calculated from the Jacobian transpose may yield values for which the motor current falls below the threshold current, which would slacken the cables and invalidate the kinematics. To fix this problem, we still calculate the motor currents found through the Jacobian transpose, and we allow this method to output up to the maximum current of 1.45 A, if needed. However, we set a condition to keep the lower current bound at 0.3 A, even if the calculations state that it should be lower. In practice, we have found that this method effectively twists the club head back to the desired angle, but the net force on the user is no longer exactly zero. During typical system operation, the net forces are small, and they do not seem to have a significant effect on the feel of the system. However, this is an aspect of system performance that needs to be evaluated by potential users, as investigated below.

5 Evaluation

Our haptic putting guidance system was demonstrated to the public at the Penn Haptics Open House on December 10, 2010. It functioned correctly for two hours with a wide variety of users. Each person was allowed to putt two golf balls, one with and one without haptic guidance on putter angle. Most people enjoyed testing the system and felt that it could contribute to mainstream society through training, therapy, or personal enjoyment.

We observed that many people seemed to putt more accurately when the haptic feedback was on, so we evaluated this aspect of our system performance in a formal study. The two hypotheses we wanted to test were as follows:

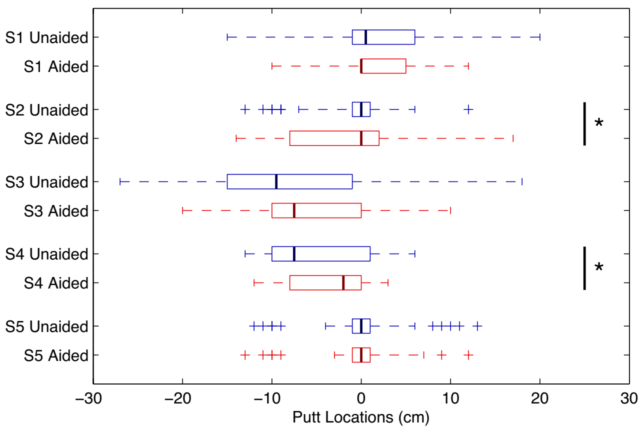

Figure 6: Box plot showing the results of the two guidance states for all five subjects. The x-axis shows the putting distance away from the target, which was located at 0 cm. The box shows the lower quartile, median, and upper quartile. The whiskers are drawn to include points that lie up to three times the inter-quartile range away from the box. The lines with asterisks signify the subjects who had significantly different variances between the two samples at $\alpha = 0.05$.

	Mean (cm)	P-value	Standard Dev. (cm)	P-value
S1 Unaided	1.48	0.94	6.99	0.11
S1 Aided	1.38		5.36	
S2 Unaided	-1.14	0.81	4.82	**0.02**
S2 Aided	-1.44		7.16	
S3 Unaided	-7.54	0.27	9.60	0.10
S3 Aided	-5.60		7.61	
S4 Unaided	-5.18	0.15	5.87	**0.003**
S4 Aided	-3.62		4.69	
S5 Unaided	-0.66	0.65	5.73	0.33
S5 Aided	-0.18		4.89	

Table 1: The means and standard deviations of the unaided and aided putting performance for all five subjects. P-values indicate the probability that the observed within-subject differences are due to chance. Guidance is seen to have no effect on the mean of any subject's distribution. Using $\alpha = 0.05$, we see that guidance affected the standard deviation for both S2 and S4, with opposite effect directions. The differences in the standard deviations for S1 and S3 approach significance, with guidance being lower for both.

1. **Accuracy:** the distribution of putts with haptic guidance has a mean error closer to zero than putts without guidance.

2. **Repeatability:** the distribution of putts with haptic guidance has a smaller standard deviation than putts without guidance.

5.1 Experimental Methods

Five subjects were recruited to repeatedly putt golf balls with our system. All participants were right-handed novice golfers between the heights of 152 cm and 182 cm. Subjects gave informed consent, and all procedures were approved by the Penn IRB under protocol #812995. Subjects were asked to use the modified putter to try to hit a golf ball toward a desired target marked 2.3 meters away from the ball. However, to prevent the subjects from overly adjusting to previous putts, we hid the target by placing a chair over the putting green and simply asked them to hit the ball as straight as possible. The study included two modes of guidance on putter head angle: unaided ($k_z = 0.0$ N·m/°) and aided ($k_z = 0.14$ N·m/°). These two modes were altered by the experimenter between putts in a preset pseudo-random order that was not made known to the subject. After each putt, the ball's deviation from the target was immediately recorded by another experimenter. After a practice session of 10 putts, subjects were asked to putt the ball 100 times, taking a break every 20 putts. Thus, each subject's quantitative data set consists of 50 unaided putt locations and 50 aided putt locations. After completing the putting task, subjects were asked to provide qualitative preferences and opinions about the putting trainer through a written questionnaire.

5.2 Quantitative Results

We tested our hypotheses by conducting two statistical tests on the data gathered for each subject. First, we tested Hypothesis 2 (repeatability) using Levene's test (`vartestn` in MATLAB with option `'robust'`), which is a robust way of determining whether two samples have equal variances. Then, we tested Hypothesis 1 (accuracy) using a t-test for equal means across samples (`ttest2` in MATLAB with the correction for unequal variances when appropriate). Box plots of all of the data are shown in Fig. 6, and the corresponding means, standard deviations, and p-values are presented in Table 1.

From the table, we can see that Hypothesis 1 was not supported by our study. The haptic putter angle guidance provided by the system did not have a statistically significant effect on the mean of any subject's putting distribution. We thus reject Hypothesis 1.

The analysis showed somewhat more interesting results for Hypothesis 2. Using $\alpha = 0.05$, Levene's test revealed that the addition of haptic guidance caused a statistically significant difference in the standard deviation of the putting distributions of subjects 2 and 4. Interestingly, S2's standard deviation increased with the addition of guidance, while S4's decreased. The remaining three subjects had lower standard deviations in the aided condition than when unaided, as we hypothesized; this difference approached significance for S1 and S3 but was not significant for S5. These findings provide mixed support for Hypothesis 2. The implemented guidance algorithm seems to affect the putting performance of some subjects, but not in the consistently beneficial way that we hypothesized. In summary, four subjects putted more repeatably when aided by the haptic putting system, one significantly so, and the fifth subject putted with significantly less repeatability.

Looking back over the study to try to understand these results, we note that S2 may not have been as naive to the study goals as the other subjects. We observed that this subject was actively trying to figure out whether the haptic guidance was on or not at each trial in the study, and thus they may not have been focusing as much as other subjects on the task of putting straight. The knowledge that haptic guidance was on might even have made this individual less careful in their putting form, or the haptic guidance may have physically disrupted the individual's natural putting form. Further study is needed to understand which types of users stand to benefit from different approaches to haptic guidance.

5.3 Qualitative Results

Ultimately, we are interested in seeing whether our haptic golf putting trainer can permanently improve a person's putting skills. Answering this question will require a larger and more complicated user study, which will involve making several adjustments and improvements to the current system. As a starting point, it is interesting to examine the qualitative reactions given by the subjects in this experiment. Three of the five subjects thought that their putting performance was improved by the system. In addition, four of the five subjects (all but S2) believed that this system could help golfers learn to putt better.

Several subjects also reported that the system made it difficult to lift the club head above a certain point. As noted in Section 3, our three-DOF planar design causes a net downward force when the user raises the club above the appropriate plane. This aspect of the haptic feedback may affect the subject's performance with or without guidance because the system does not allow a large wind up at the start of the stroke.

The main drawback of the system noted by subjects was the slight resistance one feels when moving the putter in free space; this sensation is caused by friction between the cable and the frame hole, and by the rotational friction and inertia of the motors. Several subjects reported that they thought the system performance would be improved if free space was made to feel "free-er." Another limitation comes from the physical design of our system, in which the presence of the frame forced subjects to place their feet farther from the ball than they usually would. This design flaw caused additional back fatigue for some subjects, which probably decreased their putting performance.

6 Conclusions and Future Work

We created a new planar cable-based haptic interface for the eventual goal of training users how to properly putt a golf ball. This paper describes the hardware and software design of the system, one interesting controller it can use, and a formal evaluation of that controller's effect on putting performance. We found that proportional haptic torque feedback on putter head angle did not change the central tendency of any subject's putting performance. On the other hand, it significantly affected the variance of putt locations for two subjects, one positively and one negatively; two other subjects showed beneficial effects on variance that approached significance.

In addition to the quantitative results, the user study yielded tremendous insights and inspiration for further improvements and future directions for the system. First, we want to decrease the friction in the cable system to better simulate free space. This improvement will likely be best accomplished by a mix of mechanical changes (decrease friction at the point where the cable exits the frame, reduce the bending stiffness of the cables) and software compensation (partial cancellation of friction and/or inertia). If these measures do not sufficiently reduce the resistance felt in free space, we will look into explicitly sensing cable tensions.

Second, we want to add haptic feedback to the two remaining degrees of freedom in our system, namely x and y. This modification can be implemented by setting a target location for the putter head and writing proportional controllers for both. We will likely find that naively combining force and torque outputs will often slacken the cables, so a more sophisticated approach will be developed, building on prior work in this area.

Lastly, we hope to complete an extensive user study that investigates whether this system can train people to putt better, and whether this success will translate to improved putting performance with a normal putter. The envisioned user study will separate subjects into three groups for training: no haptic guidance, haptic guidance, or haptic disturbance. We are particularly interested in the potential benefit of haptic disturbance given the encouraging recent findings of [7], as disturbances may motivate subjects to try to do improve their form, whereas haptic guidance may encourage subjects to become reliant on the system.

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