MAE 219 Project Report: Motor Rehabilitation Device

Eesa Khan, Logan Reuter, Mukta Phadnis, and Sam Dang

***Abstract*— Motor rehabilitation therapy or devices are not always accessible or affordable for patients who have suffered from a stroke. In this paper, a cost-effective haptic system with force feedback capabilities is proposed as an accessible alternative for at-home therapy. This haptic system focused on helping users re-learn the critical task of opening a door, with applications for a jar as well, by integrating rotational and translational movements with force feedback.**

I. INTRODUCTION

Patients who suffer from a stroke, can often lose the motor skills to perform basic tasks in their everyday lives. Rehabilitation can take months or even years, and require countless sessions with physical therapists, which may not be financially accessible to all patients. Haptic systems, with their ability to provide force feedback, have become a highly explored area to assist in rehabilitation for patients. They offer the opportunity to create systems for physical therapy that can be used from home, increasing accessibility, personalization, and maybe even effectiveness when compared with conventional physical therapy options. In this paper, a haptic system to assist in regaining the ability to perform an often overlooked everyday task, of opening and closing doors, is proposed. A generic approach to this method was taken, implementing a simple rotating motion in parallel with a translational motion, both equipped with force feedback. This implementation allows for further uses in applications such as relearning to open jars or turning steering wheels. The jar implementation was explored during this project, but the door implementation will be the main focus, due to it being the main motivation behind the project.

II. BACKGROUND

A. Related work

Previous work on the topic of rehabilitating the motor functions required for opening doors has focused mainly on twisting the doorknob itself, as opposed to the full task of opening the door. Lambercy (et. al) [1] designed a two-degree-of-freedom doorknob system, which focused on the user learning to grip the doorknob, and twist it, which they found was able to accelerate user improvements. Zhou (et. al) [2] explored new ways to detect user input forces on a haptic knob using the current from the attached motor, but again this research seemed to solely focus on the rotational motion of a doorknob.

Other work such as that done by Feick (et. al) [3] looks at haptic knobs in the context of virtual environments and the gaming industry. This paper and others similar to it focus on outputting extremely realistic forces through the knob, to enhance user experiences in virtual reality. While these methods of outputting precise forces are useful, they do not seem to have been utilized in the context of physical therapy. Even though the rotation of the knob is an important factor for opening a door, it is not solely enough to enable patients to conduct the task.

The research done by Oblak (et. al) [4] seems to be some of the most relevant to what is trying to be done here. They described how much of the previous research on wrist and arm rehabilitation, only allowed for one to be focused on. They themselves created a two-degree-of-freedom system, which allowed for wrist rotation and arm flexion training, which they described as being cheaper than any other system currently available. This system was however very general, and didn't allow for the user to work on specific tasks, but rather just work on improving overall wrist and arm movements. In this framework, we seek to create a system that focuses on interacting with doors specifically, and also makes the system as inexpensive as possible, to increase the accessibility for patients.

It is clear that not every doorknob requires the same force to turn or open every door. The literature does not seem to cover this topic in much detail, so finding ballpark values for what a system should aim to output required some thought. According to Lori Greene [5], there are guidelines that doors have to abide by to ensure them being accessible to everybody. These guidelines include the door should require less than 66.7 N to open, and the doorknob less than 0.315 N-m. However, the force requirement of 66.7 N was likely obtained from an actual door, so our system will aim to achieve a force at the lower end of this spectrum. These values will be helpful in the design of our system. By combining pieces from previous literature, we aim to create an inexpensive, easy-to-use haptic system that can assist users, from start to finish, in regaining the ability to open doors.

III. DESIGN

The system proposed in this paper was planned and designed to have as low of a manufacturing cost as possible by utilizing basic manufacturing methods, materials, and off-the-shelf parts. This is motivated by the goal of making this rehabilitation system accessible to all patients. Three-dimensional (3D) printing is one of the most accessible forms of manufacturing, due to high-quality printers becoming attainable within a household. The rehabilitation system designed here is not subjected to high intensity, and is thought to often be used with many breaks, which led to the conclusion that high temperatures from the electronics would not be an issue. In addition to this, the torques and forces

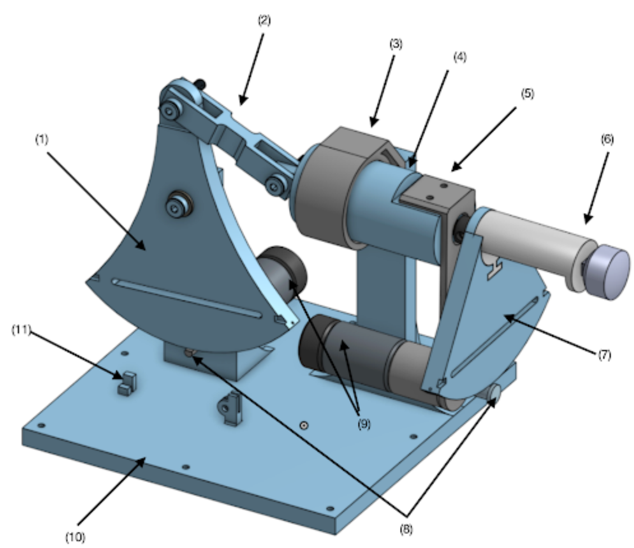

Fig. 1. Motor Rehabilitation Device

which the system would have to withstand were deemed to be small enough that 3D printing materials at a standard infill would be able to hold up. This allowed for 3D-printed PLA to become the main material when manufacturing the system. The computer-aid design (CAD) of our system is illustrated in Fig. 1.

A. *Components*

- (1) This component allows for the motor's torque to be translated to lateral forces, which will function as the mechanism used to simulate the opening and closing of a door. Inspiration for this piece was taken from Professor Morimoto in her MAE 219 class at UC San Diego. There, they had designed a Hapkit, which translated torques into translational forces for haptic feedback. Seeing as their system worked so well, it was decided to change the dimensions of their system, and utilize the same mechanism for this application. Details on the design and analysis can be found in her course reserves [6].
- (2) Inspired by a piston, this component was designed to push along the slider, linearly, even though the top of component one will be rotating and changing its vertical position relative to the base plate.
- (3) This piece functions as a guide for the slider. Simply put, it restricts the motion of the slider to purely translational, allowing for the user experience of pushing and pulling a door to not be impeded by vertical movements. It also acts as a support to counteract the moments which will be applied by the weight of the rotational mechanism.
- (4) This component is the slider, which takes the linear forces from component (1) and allows the user to feel it. On the back end, it connects to component (2), which pushes and pulls it, and on the front it screws directly onto component (5).
- (5) This I-beam attaches the translational feedback half of the system to the rotational feedback half. The rotational feedback motor screws directly into this to support it.
- (6) Twisting knob. The end of this component is where the user will be holding on to. The user will be able to twist and pull / push this piece, allowing them to interact with the system as necessary.
- (7) Same as component (1), just with a smaller radius since the rotational feedback does not need to be amplified as much as the translational feedback.
- (8) These two pieces are just simple capstans. A wire is strung through one side of components (1) and (7), wrapped around the capstans three times, and then strung through the other end of components (1) and (7).
- (9) There were two different motors used here. The one on the left, which provided translational motion, is a standard 12V motor. This motor doesn't have an encoder, so a magnet was attached to the pulley, and a Magneto Resistive (MR) sensor was used to track rotations. The motor on the right is another standard 12V motor with a 1:20 reduction ratio, and has an encoder, so its position was directly taken from that.
- (10) The base plate was printed with supports that the translation motor, and the guide are attached to. It was also printed with holes on its edges, so later if needed, different supports could be attached to allow the system to lie on either one of its sides.
- (11) Holder for the microcontroller. The microcontroller of use here will be a Hapkit, from Professor Morimoto's MAE 219 class. It is a modified Arduino UNO, which also includes the MR sensor needed for the first motor, which simplifies the design significantly.

To attach all of these components together, M3 screws and nuts were used in addition to basic fasteners. Both of these are simple pieces, and were ordered directly from Amazon, as well as taken from the lab in which this system was designed. The exact dimensions of all the components are not listed here, seeing as the design is fairly simple, and can easily be scaled up or down depending on specific needs. This description merely seeks to explain the basics of the mechanism used for this system to function.

In addition to the physical system, software was needed to simulate the virtual environments which the user would feel. The C language, C++ specifically, was utilized to write the code for controlling the physical system. The physical system is capable of providing the users with two training modes: Haptic Guidance and Haptic Hindrance. In the Haptic Guidance mode, users are expected to be in the process of re-learning the motion of opening a door, resulting in the system outputting forces to assist the user in the motion. In contrast, in the Haptic Hindrance mode, the users are expected to want resistance during the motion to further strengthen their motor skills; this is achieved by outputting forces opposing the user's motion. The algorithms used to simulate these environments are explored further below.

B. Abbreviations and Acronyms

F_{dh} : *Door handle force (rotational)*
F_{dr} : *Door force (translational*
K_{dh} : *Door handle stiffness*
K_{dr} : *Door stiffness*
$iniRpos$: *Initial rotational position*
$iniTpos$: *initial translational position*
$userRpos$: *User rotational position*
$userTpos$: *User translational position*
$targetTpos$: *target translation position*
C_{smth} : *Smoothing constant (different for each cases)*
F_{jT} : *Jar twisting force (rotational)*
F_{jO} : *Jar opening force (translational*
K_{jar} : *Jar stiffness*
$slipPos$: *Jar slip position*
$C_{jO(Assist)}$: *Smoothing constant for jar assistance*
$C_{jO(Ressist)}$: *Smoothing constant for jar hindrance*
$resistiveHandleScalar$: *scaling constant*
$F_{constant}$: *constant force*

C. Equations

Task 01: Opening a door

a. Guidance

$\mathrm{F}_{dh} = K_{dh} * |iniRpos - userRpos - C_{smth}|$

$F_{dr} = K_{dr} * |(targetTpos - C_{smth}) - (userTpos - initTpos)|$

$\underline{a.Hindrance}$

$K_{handle} = K_{dh} * resistiveHandleScalar^2$

$F_{dh} = K_{handle} * |iniRpos - userRpos| + C_{smth}$

$K_{door} = K_{dr} * resistiveHandleScalar^2$

$F_{dr} = K_{door} * |(targetTpos - C_{smth}) - (userTpos - initTpos)|$

Task 02: Opening a jar

a. Guidance

$\mathrm{F}_{jT} = F_{constant}$

$F_{jO} = C_{jO(Assist)}$

$\underline{a.Hindrance}$

$F_{jT} = K_{jar} * |iniRpos - userRpos - slipPos|$

$F_{jO} = C_{jO(Resist)}$

D. Algorithms

Algorithm 1 Haptic Guidance Opening a Door

if user's angular position != desired position **then**
  SET linear force to prevent linear motion
  SET rotational force to $\mathrm{F}_{\text{dh-guidance}}$
else
  SET rotational force to a constant force
  SET linear force to $\mathrm{F}_{\text{dr-guidance}}$
end if

Algorithm 2 Haptic Resistance Opening a Door

if user's angular position != desired position **then**
  SET linear force to prevent linear motion
  SET rotational force to $\mathrm{F}_{\text{dh-resistance}}$
else
  SET rotational force to a constant force
  SET linear force to $\mathrm{F}_{\text{dr-resistance}}$
end if

Algorithm 3 Haptic Guidance Opening a Jar

if user's angular position != slip position **then**
  SET linear force to prevent linear motion
  SET rotational force to $\mathrm{F}_{\text{jT-guidance}}$
else
  SET rotational force to 0
  if user's linear position less than seal release distance **then**
    SET linear force to 0
  else
    SET linear force to $\mathrm{F}_{\text{jO-guidance}}$
  end if
end if

Algorithm 4 Haptic Resistance Opening a Jar

if user's angular position != slip position **then**
  SET linear force to prevent linear motion
  SET rotational force to $\mathrm{F}_{\text{jT-resistance}}$
else
  SET rotational force to 0
  if user's linear position less than seal release distance **then**
    SET linear force to 0
  else
    SET linear force to $\mathrm{F}_{\text{jO-resistance}}$
  end if
end if

In each scenario, the user's angular position was found using the relationship between the current encoder counts and the total counts per revolution of the motor. The user's angular position is then utilized to find the initial angular position as well as the desired/target angular position. Once the positions are calculated, the distance between them is determined to set up the right conditions for each task. The specific conditions for each mode are listed in the algorithms above. In the door opening task, the door handle must finish rotating before triggering the translational motor for pushing the door in and out. At the finish position, a hard stop was implemented using a constant force value. Similarly, in the jar opening task, an angular slip position was defined to ease out the resistive force in order to render the "slipped" sensation and allow the user to begin to feel the translational haptic feedback. In addition to this, the jar condition required a check to see if the user had moved a specific distance linearly. When a lid is fully removed from a jar, there is no longer a linear force acting on the lid. This value was used in determining when the user would no longer have to feel a force linearly from the jar. In addition to the fundamental equations above, the actual guidance and hindrance states require many additional components and tweaks (conditions, hard-stops, delays, etc.) in order to function correctly. Other important variables such as stiffness, delays, and smoothing constants were found through trial and error. Damping forces were not included as it would introduce a lot of noise as well as instabilities. The resistance mode also included various levels of difficulty. This was accomplished by having the user input a resistance level value that was an integer value ranging from 1-10. This value was used to scale the stiffness values used in the equations above to create increasingly difficult levels of resistance for the user.

IV. METHODS

A pilot user study was run to identify the absolute threshold for the assistive mode in the doorknob task using the method of constant stimuli. The haptic feedback for this mode was the most subtle, so a threshold needed to be determined where most users would be able to feel the haptic feedback. Using this method, a set of 5 comparison stimuli was decided to center around a nominal stimulus. The nominal value was initially identified using trial and error over a wide range of K_{dh} and K_{dr} values. The user was then asked if they felt the stimulus. The results of this help determine the minimum force levels required for a user to feel assisted and guided through the motion which can be implemented and further refined for the device when running a full user study. Additionally, these values were found to be applicable to the jar's configurations.

Looking to the future, a full user study would need to be conducted to determine the effectiveness of this system in practical applications. The following would be performed under the assumption that a pool of physical therapy patients with limited upper limb mobility, either from strokes or similar conditions, has been found. Initially, each patient would be put through a series of tests to determine their baselines. This could be done by attaching a force sensor to this system and measuring the maximum translational and rotational forces each user can initially output. Once the baseline has been established, the user pool can be split into three different groups. One that will go through conventional physical therapy processes, one will use our designed system, and the last group will not participate in any motors rehabilitation training. From here, each group can be observed for 2-3 weeks, and put under similar training conditions. For the group utilizing the system, they can work their way through the difficulty ranks, starting from assistive, and increase as far as they can into the resistive levels. Once the training period is over, the initial tests used to determine the baseline can be conducted again, and each user's data can be compared from pre-training to post-training. This will allow for us to check if the system has the ability to improve user performance when using it for a period of time, additionally we could also check if the system can produce greater rates of rehabilitation when compared with conventional methods. Currently, this is being explored as the next steps to test the actual effectiveness of this system.

V. RESULTS

Once fully functional, the system was found to successfully perform the desired tasks. The conversion from rotational motion to translational functioned as desired, and the capstan system amplified the forces and torques felt by the user to values within the ranges that needed to be achieved. The system was easily assembled, and was also inexpensive to make, falling in the range of 40 dollars when completed. Both translational and rotational feedback were able to be controlled independently or in sync utilizing the written software, and the UI was successfully designed to allow for the user to operate the system easily. The assembled design allowed for 3 inches of lateral translation, and 120 degrees of rotational translation by the users. These were determined to be adequate in supporting the full twisting motion, as well as the extending motion from the elbow, which is approximately 20 degrees. Looking at the forces and torques that the system can output, an identical method as used by Professor Morimoto in her MAE 219 class will be used. As outlined in the notes from Lecture 04 [7], the translational force, and output torque from a motor-capstan system as implemented here can be found in Equations 1 and 2 respectively. This leads to the maximum translational force output to be 4.6 N, and the maximum torque which the user can feel equal to 0.183 N-m. The physical parameters of the system are illustrated in Table I below.

$$F_{Translational} = \frac{r_{sector}}{r_{handle} r_{pulley}} \tau_{pulley} \textit{ (Eq. 1)}$$

$$\tau_{sector} = \frac{r_{sector}}{r_{pulley}} \tau_{pulley} \textit{ (Eq. 2)}$$

TABLE I
PHYSICAL PARAMETERS OF SYSTEM

	Translational	Rotational
r_{pulley}	0.005m	0.0175m
r_{sector}	0.076m	0.064m
τ_{pulley}	0.0183Nm	0.05Nm
r_{handle}	0.06m	N/A

TABLE II

ASSISTIVE ABSOLUTE THRESHOLD OF K_{DR} AND K_{DH}

K_{dr} Value (N/m)	User 1: Did you feel the stimulus for K_{dr}?	User 2: Did you feel the stimulus for K_{dr}?	K_{dh} Value (N/m)	User 1: Did you feel the stimulus for K_{dh}?	User 2: Did you feel the stimulus for K_{dh}?
450	Yes	Yes	0.0000130	Yes	Yes
350	Yes	Yes	0.0000125	Yes	No
250	Yes	Yes	0.0000120	Yes	No
150	Yes	No	0.0000115	No	No
50	No	No	0.0000115	No	No
Absolute threshold: 150			Absolute threshold: 0.0000120		

Table II shows the results of the pilot user study to identify the absolute threshold values of K_{dh} and K_{dr}. After collecting sufficient samples to get significant results from statistical analysis, the absolute threshold would be the value of K_{dh} and K_{dr} where 50% of the users are able to feel the stimulus. The absolute threshold value from these results for K_{dr} was 150 N/m, and 0.0000120 N/m for K_{dh}. The implemented K_{dh} and K_{dr} values were chosen to be slightly higher than this absolute threshold to ensure that any users would feel the motion guidance from the device.

VI. DISCUSSION

When performing preliminary tests with other users, the general sentiment was that the system felt realistic and smooth, validating the design that had been chosen. Even with the limited translational motion that the system currently allows for, users reportedly described having their elbow engaged, which was our target. It is clear that the 3 inches of translational motion is not enough to accurately simulate a door, but the elbow engagement during the task proves that this system can stimulate the muscles that are being targeted. The rotational motion of 120 degrees is realistic when it comes to simulating a doorknob, due to the fact that doorknobs do not require a full 180-degree rotation, and often in the range of 90-120 degrees will suffice.

Once the pilot user study had been completed, it was made a priority to determine whether the values found were actually noticeable to users outside the study as well. The values of K_{dr} = 175 N / m and K_{dh} = 0.00001225 N / m were implemented in the door simulation and a new set of users was asked to interact with the device. The new users, all described the assistive modes as noticeable, confirming the values found in the pilot study.

In addition to the positive feedback received from preliminary testers of the system, the force and torque which the system are capable of outputting fall within the range of what was set out to be achieved. Earlier, it was outlined that the standard force to open doors should require less than 66.7 N, with around 5 N being more of an ideal goal. The maximum linear force which this system, was able to produce was 4.6 N, which according to the previous statement, should be able to simulate a door quite well. On the rotational side, the maximum torque that is required to turn a door handle has previously been outlined as 0.315 N-m. Our system was able to output 0.183 N-m. While this value is not close to the literature value, it is still within a reasonable threshold, which will allow for realistic door simulations to be practiced on by users.

VII. CONCLUSIONS

Based on the data received from users, and performed tests, our design met the initial targets of a low-cost, easily manufacturable haptic system that can simulate both the rotational and translational sensations of opening a door. After conducting a pilot study on the magnitude of force feedback which should be implemented for assistive users, both the resistive and assistive modes of force feedback were noticeable to users, and were seen to have the potential to aid in motor rehabilitation. The system was able to produce 3 inches of translational motion in addition to 120 degrees of rotational movement. While the translational motion is not currently enough to accurately simulate a door, users'feedback indicated that elbow joints were being engaged by the system, which is what is desired of the system. The maximum force the system can output is currently 4.6 N, which is far off from the literature value of 66.7 N. However, as mentioned above, the 66.7 N force was likely recorded from a regular sized door. The final torque outputs were lower than the original goals, however, the literature around torque values for these systems did vary, and the torques the system is capable of outputting reportedly felt realistic by the users.

During preliminary tests, a number of areas of improvement became apparent. The largest area for improvement was determined to be the adjustment of the translational mechanism. This is thought to be pursued by adding a key slot into the slider and a key to the rotational capstan, which would allow for the rotational motor to be moved onto the base plate. The key slot would allow the slider to move translationally through the capstan while making the two move together rotationally. This change would make the design more stable and remove unnecessary weight from the slider. Through this adjustment, a number of the issues encountered during testing can be resolved. One of these issues is friction between the shaft collar and the 3D-printed parts, which caused the handle to unscrew itself after extended usage. Other issue that need to be addressed is the friction between the slider and the guide, as well as the generally loose tolerancing, which prompts the entire rotational mechanism to rotate slightly when trying to turn higher torques. These issues can be mitigated by decreasing tolerances, changing materials to metal, or shifting to SLA printing instead. Finally, the rotational capstan was noticed to slip under high loads which would cause issues with incorrect encoder values being read. In order to solve this problem, a better tensioning mechanism would be implemented. While the design may not be consumer ready, this system shows that the idea is viable for the desired application, and with minor modifications, can become production ready.

ACKNOWLEDGMENTS

We would like to thank Professor Morimoto and teaching assistant Robert Bloom for their expert advices as well as encouragement throughout this project.

REFERENCES

[1] O. Lambercy, L. Dovat, R. Gassert, E. Burdet, C. L. Teo and T. Milner, "A Haptic Knob for Rehabilitation of Hand Function," in IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 15, no. 3, pp. 356-366, Sept. 2007, doi: 10.1109/TNSRE.2007.903913 .https://ieeexplore.ieee.org/document/4303105.

[2] L. Zhou, K. K. Ang, C. Wang, K. S. Phua and C. Guan, "A novel hand strength assessment method integrated into haptic knob for stroke rehabilitation," 2013 IEEE Symposium on Computational Intelligence in Rehabilitation and Assistive Technologies (CIRAT), Singapore, 2013, pp. 1-4, doi: 10.1109/CIRAT.2013.6613815. https://ieeexplore.ieee.org/document/6613815

[3] Martin Feick, André Zenner, Oscar Ariza, Anthony Tang, Cihan Biyikli, and Antonio Krüger. 2023. Turn-It-Up: Rendering Resistance for Knobs in Virtual Reality through Undetectable Pseudo-Haptics. In Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23). Association for Computing Machinery, New York, NY, USA, Article 11, 1–10. https://doi.org/10.1145/3586183.3606787

[4] J. Oblak, I. Cikajlo and Z. Matjačić, "Universal Haptic Drive: A Robot for Arm and Wrist Rehabilitation," in IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 18, no. 3, pp. 293-302, June 2010, doi: 10.1109/TNSRE.2009.2034162. https://ieeexplore.ieee.org/abstract/document/5290020.

[5] https://idighardware.com/2014/03/decoded-operational-force-for-door-hardware/

[6] MAE 219 Course Reserves

[7] lecture04_kinesthetic_devices_inclass_MAE219_Fall_2024.