Short Paper

A Handheld Gyroscopic Device for Haptics and Hand Rehabilitation

Namita Anil Kumar, *Member, IEEE* and Pilwon Hur, *Member, IEEE*

***Abstract*—We propose a novel, gyroscopic device for haptics and hand rehabilitation, named *Gymball*. It consists of a fully actuated rotor-gimbal assembly encased in an easy-to-grip appealing design. When held, the device generates a gyroscopic torque which causes the user's hand to move about the wrist. Interviews with occupational therapists, simulations, and proof-of-concept models helped determine the design specifications of *Gymball*. Compared to the existing gyroscopic devices, *Gymball* has the following advantages. (i) A smaller form-factor with better user appeal while achieving 0.5 Nm torque. (ii) A wire entanglement-free design allowing complete rotations of the rotor-gimbal assembly. (iii) Negligible rotary imbalances owing to a symmetrical design, resulting in haptic signals with minimal vibratory noise. In this paper, we detail the design and analysis of the device. A feasibility study was conducted to validate prospect of using the device for haptic feedback or therapy. Specifically, the study focused on (i) whether the gyroscopic torque generated by the device can passively move the user's hand about the wrist and (ii) whether the produced hand motion can be controlled. The results show that *Gymball* can successfully generate about 7° of hand oscillations. The amplitude and frequency of the hand oscillations can be controlled using the speed of rotor and gimbal.**

Index Terms—Hand rehabilitation, haptic interface, handheld device, gyroscopic torque, solid modeling.

I. Introduction

From the simple vibrations of a mobile phone to force feedback in powered-wheelchair joysticks, the application of haptics is far reaching. The dynamic growth in these fields of application has increased the demand for better user experiences [1]. Researchers have attempted to satisfy this demand by increasing the information contained in sensory feedback using unconventional feedback mechanisms like skin-stretch and force-feedback. In the field of human rehabilitation, there is a strong demand for at-home rehabilitation services [2]–a demand that has increased ever-so-more with the onset of COVID-19. We propose a novel hand-held device, called *Gymball*, that can be used for force-feedback or occupational hand rehabilitation therapy.

While vibro-tactile feedback is the most popular implementation of haptic feedback, studies such as [3], [4] used skin-stretch and force feedback to convey information with multiple properties (e.g. magnitude and direction). Despite the advantages of force-feedback, the wide adoption of devices utilizing it is limited because they are not portable. Typically, force-feedback devices involve a joystick that is anchored to a fixed surface.

On the other hand, researchers have been attempting to design portable force-feedback devices utilizing a gyroscope [5]–[8]. These devices incorporate an actuated rotor-gimbal assembly capable of imposing a controlled torque on the user's hand. The aim of the product in [5] is to counter hand tremors for those suffering from Parkinson's disease using the generated gyroscopic torque. But the device is in the initial stages of production and no data on its performance is currently available. Additionally, the device's limited torque prevents greater adoption from occupational therapy wherein we wish to generate a torque strong enough to passively move the hand about the wrist.

The studies [6], [7] proved the ability to control the torque imposed on the user's hand. A potential downside of both studies is their asymmetric design, which can lead to unwanted vibrations that can disrupt user experience. Additionally, the output torque of these devices is mostly limited to avoid exacerbating the unwanted vibrations. In this paper, we determined the demerits of an asymmetrical design in a proof-of-concept model (detailed in Section II). It is also unclear how studies [6], [7] addressed the issue concerning rotor wiring, i.e., how to avoid wire entanglement while the rotor precesses. We solve this issue using slip-rings (detailed in Section III). The study in [8] incorporates gyroscopic torque-based feedback in two-handed gaming consoles. These studies served as inspiration for our proposed device, *Gymball*, which is a one-handed gyroscopic device with a symmetrical design.

In the rehabilitation field, studies have shown that a device's user appeal is directly tied with entertainment value [9], which is vital because many devices are at risk of abandonment by users [10]. As such, researchers have attempted to improve entertainment value of rehabilitation products by incorporating gaming into therapy. Studies such as [11] successfully designed Nintendo Wii based therapies to improve motor functions in stroke patients. Motivated by the nascent growth in entertaining hand rehab devices, user appeal of the device played a significant role while designing *Gymball*, as did its form-factor.

Our main contributions include a novel design that mitigates undesired vibrations, delivers higher torque, eliminates wire entanglement, and better form-factor compared with the state-of-the-art. We discuss the working principle and design needs of *Gymball* in Section II substantiated with results from a proof-of-concept model. Section III details the design of the device while Section IV presents the design analysis. The feasibility study conducted with the *Gymball* is in Section V with results in the following section.

Manuscript received September 18, 2021; revised November 24, 2021; accepted January 13, 2022. Date of publication January 21, 2022; date of current version March 18, 2022. This work was not supported by any organization. This article was recommended for publication by Associate Editor Dr. Junji Watanabe and Editor-in-Chief Prof. Domenico Prattichizzo upon evaluation of the reviewers' comments. *(Corresponding author: Pilwon Hur.)*

Namita Anil Kumar is with the Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843 USA (e-mail: namita.anilkumar@gmail.com).

Pilwon Hur is with the School of Mechanical Engineering, Gwangju Institute of Science and Technology, Gwangju 61005, South Korea (e-mail: pilwonhur@gist.ac.kr).

This article has supplementary downloadable material available at https://doi.org/10.1109/TOH.2022.3144581, provided by the authors.

Digital Object Identifier 10.1109/TOH.2022.3144581

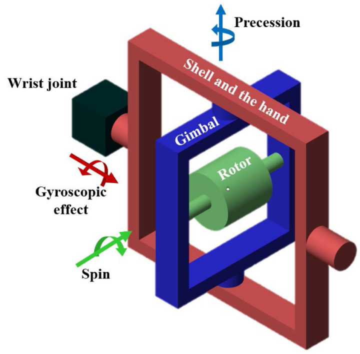

Fig. 1. Schematic of a hand-held gyroscopic device.

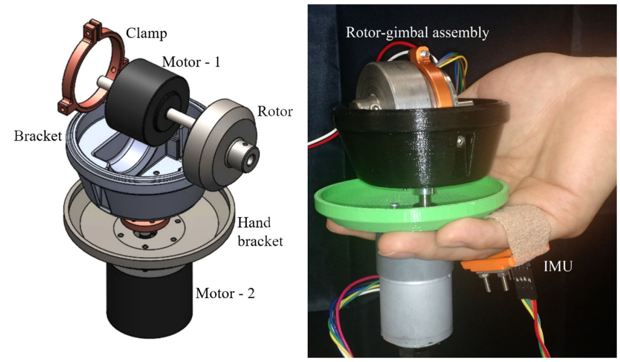

Fig. 2. Proof-of-concept model. LEFT: A CAD model of the device. RIGHT: The experimental setup.

II. Working Principle and Design Needs

Gymball consists of a fully actuated rotor and gimbal assembly encased in an oblong shell. A schematic of the device is shown in Fig. 1. The simultaneous action of the rotor and gimbal gives rise to a gyroscopic torque that acts on the hand grasping the device. In this section, we enumerate the design needs of the device (N1 - N9). These need numbers will be referred through the rest of the paper. To successfully use such a device for hand rehabilitation or haptic feedback, the hand movement provoked by the gyroscopic torque should be repetitive and controllable. Interviews with physical and occupational therapists also revealed that the *Gymball* can be used in two therapeutic exercises that vary based on the user's restriction to the imposed gyroscopic torque. If the user posed no restriction, the hand would be passively moved within its range-of-motion. Such an exercise can prospectively relax hand muscles and help combat spasticity [12]. On the contrary, if the user restricted any form of hand motion, it could lead to strengthening of hand muscles and improvement of muscle co-ordination [13]. This resulted in two design needs: (N1) the generated torque should passively move the hand about the wrist, (N2) the motion generated should be manipulable. Furthermore, for rehabilitation, aspects of the design must be based on Activities of Daily Living (ADL). Some ADL include carrying a water bottle from a vending machine (weighing approximately 500 g) and opening a jar (requiring about 0.7 Nm [14]). These respectively formed our weight (N3) and torque design specifications (N4). The interviewees also stated the need for (N5) an appealing design to avoid device abandonment and (N6) a portable form-factor.

To test the working principle and determine other design needs, we conducted a proof-of-concept test. Fig. 2 shows the experimental setup of the proof-of-concept model. While Motor-1 spun the rotor, Motor-2 precessed the rotor. The resulting gyroscopic torque acted upon the hand holding the Hand bracket. An Inertial Measurement Unit (IMU) affixed to the hand measured the angular displacements. Further testing led to observations regarding the effects of rotor and gimbal's motion on the nature of the generated hand motion. (i) The extent of the hand's movement could be controlled greatly by the rotor and gimbal's rotational speed. (ii) The gimbal's oscillation frequency dictated the frequency of the hand's oscillation. These two results helped assure the satisfaction of needs (N1) and (N2). (iii) Finally, it was observed that rotary imbalances led to vibrations which affected the user's ability to grip the device. This final result helped formulate two needs: (N7) rotationally symmetric design to avoid vibrations, (N8) an easy-to-grip design. Finally, the device must be (N9) wire-entanglement free–a challenge with fully actuated gyroscopes.

TABLE I
Estimated Gyroscopic Torque for Different Rotor Materials

Material	Weight of the final device (g)	Estimated torque (Nm)
Alumide	535.53	0.30
Aluminum	540.42	0.40
Steel	640.42	0.73

III. Design of the Device

With 0.7 Nm as the target torque (N4), the inertias of the rotor and gimbal were suitably determined. To calculate the desired inertial properties of the device, a dynamic model (shown in Fig. 1) was created in Simscape (version 2016, Mathworks, Natick, MA). The device along with the hand was modeled as a five degree of freedom system: (i) Wrist pitch q_1 - flexion & extension, (ii) Wrist yaw q_2 - radial & ulnar deviation, (iii) Wrist roll q_3 - pronation & supination, (iv) The precession of the rotor and-gimbal assembly q_4, (v) Rotor spin q_5. The latter two degrees of freedom are actuated. The attached supplemental document contains images of the Simscape simulation. The rotor speed was 2800 rpm and gimbal speed was 240 rpm. Assuming the material of the rotor and gimbal to be Alumide (a plastic with dispersed aluminum particles [15]), the simulated gyroscopic torque acting about the wrist was estimated to be 0.3 Nm. Note that the generated torque would be 0.5 Nm if the gimbal speed is 400 rpm. Table I depicts how the resulting gyroscopic torque can be increased by changing the material of the rotor. The table also reports the total weight of the device. Although the magnitude of the torque generated using a steel rotor matches that stated in the target specifications, the weight (644.866 g) fails to meet the requirement (N3). To strike a balance between needs (N3) and (N4), Alumide was selected as the material for the rotor and gimbal assembly. The inertias derived from the simulation served as guidelines while designing the device.

The rotor-gimbal assembly (Fig. 3) is enclosed in an oblong shell that has finger holds to facilitate a comfortable cylindrical grip on the device (N8). This aspect is further investigated in Section IV. Note the mathematical model envisioned a spherical grip. But owing to design challenges the grip was revised. Further, it was understood that users with an inability to grasp objects, due to spasticity, must utilize a tensioned glove to operate *Gymball*. Keeping in mind the immediate American market, the shell was designed to resemble an American football to increase user appeal (N5).

The rotor and gimbal were actuated by frameless 40 mm Maxon EC-i outer rotor brushless DC motors (Maxon, Sachseln, Switzerland).

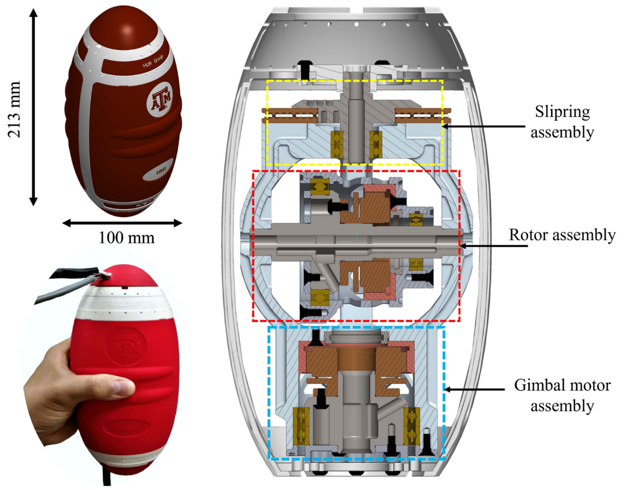

Fig. 3. LEFT: *Gymball* CAD model and fabricated device. RIGHT: Major components.

Frameless motor kits enabled custom designing the motor housing to assure (N7) rotational symmetry and to avoid imbalances. Outer rotating (out-runner) motors were selected to increase rotational inertia and achieve the desired torque (N4). The motors were driven using DEC 24-2 Maxon drivers. The housings of the motors were custom designed to have inertias similar to those determined by the mathematical model. The supplemental document presents the inertia tensors for the rotor and gimbal assembly. Most important to note is the minimal off-diagonal elements (< 0.37 Kgmm^2)–a sign of rotational symmetry (N7). The housings incorporate a webbed structure to reduce weight while attaining the desired intertias. Another benefit of the webbed structure is that they allow air-cooling of the motor. Holes at the top of the external shell vent any built up heat. Internal channels were carved along the motor shafts and the gimbal housing for guiding the motors' stator wires. Finally, a slip-ring assembly was used to transmit power and signals from the external control module to enable wire entanglement-free precession and spin of the rotor (N9). The slip-ring assembly enforces a limit of 400 rpm on the gimbal's speed. A set of angular contact bearings, placed at the lower end of the gimbal, handles both the radial loads due to precession and the axial loads due to the weight of the rotating components. All parts were fabricated using selective laser sintering (an additive manufacturing process) to ensure fine surface finish and dimensional accuracy.

Overall, *Gymball* strikes a balance among weight (N3), torque (N4), and form-factor (N6) requirements weighing 536 g, estimated to produce 0.5 Nm, and with 10 cm diameter and 21.3 cm length. On the contrary, the product in [6] can produce 1 Nm torque, but weighs 734 g and is about 36 cm long. The product in [7] is compact and weighs 288.5 g, but can only produce 0.052 Nm.

Presently, the control inputs to the motor drivers are provided using a Teensy 3.6 micro-controller. An Inertial Measurement Unit (IMU, MPU-9250, Sparkfun, Boulder, CO, USA), mounted on the top of the *Gymball*, measures the angular deviations of the hand holding the device. The data gathered from the IMU is filtered using a complementary filter. Fig. 4 depicts the aforementioned components. The setup presented in Fig. 4 will also be used in the feasibility study (Section V). For the time being, commands to the *Gymball* are issued using a computer. It should be noted that any function conducted by the computer can be carried out by the Teensy micro-controller, making the system portable. A micro SD card within the Teensy can be used to store the filtered motion data from the IMU.

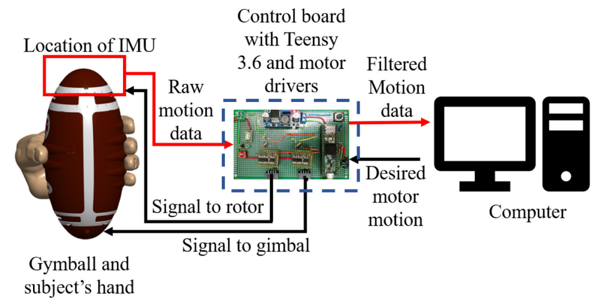

Fig. 4. Experimental setup for the feasibility study.

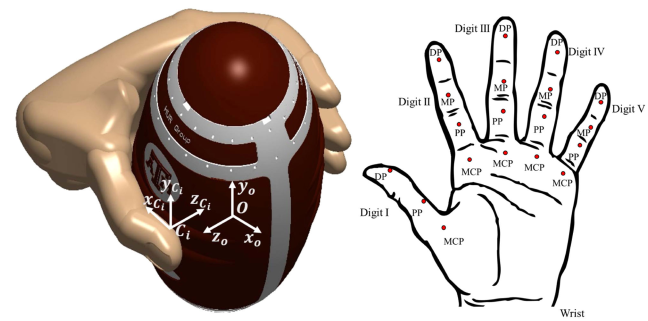

Fig. 5. LEFT: CAD model of a hand holding the device. A contact point C_i placed at the thumb's distal phalanx (DP). RIGHT: The contact points at all DP, Medial Phalanx (MP), Proximal phalanx (PP), Metacarpal phalanx (MCP).

IV. Analysis of the Design

Dynamic simulations were carried out in Solidworks (SolidWorks 2016, Dassault Systèmes, Vélizy-Villacoublay, France), to attest the structural integrity of the components. During the simulation, the rotor and gimbal speed were 3000 rpm and 400 rpm, respectively. A high factor of safety (≥ 2) ensured the structural stability of the device.

As stated earlier, the manner of gripping *Gymball* was designed to be a cylindrical grip. Such a grip is considered to be a power grip and is often practised in rehabilitation therapies and ADL. To ensure that the device could be gripped comfortably (N8), close attention was duly paid to the distribution of the forces imposed by the device on the palm. A major contributing factor to said distribution is the design of the shell's grooves (finger holds) since they assert the positioning of the user's fingers. It was assumed that a cylindrical hold is suitable if it respects the force distribution trends reported in [16]–[18]. These forces will act at every point of contact between the hand and the device. Per [16]–[18], the thumb would have to withstand most to the normal forces imposed on the hand. Further, among the proximal, medial, and distal phalanx of each finger, the distal phalanx is generally subjected to more normal force compared to the others during a power grip. A nonlinear optimization problem was solved to theoretically estimate the forces imposed by *Gymball* on the user's hand. The following details the approach adopted and its results.

To determine the points of contact, we built a CAD model of a hand holding the device, which can be seen in Fig. 5. The hand model used can be found at [19]. The fingers were aligned along the grooves designed about *Gymball*'s shell. Once aligned, information regarding the orientation of each contact point with respect to the center of the object was gathered. If $O \in \mathbb{R}^3$ is the center of the device, then the orientation of a contact point $C_i \in \mathbb{R}^3$, for $i = 1, \ldots, 19$, is given by the position vector $p_{OC_i} \in \mathbb{R}^3$ and rotation matrix $R_{OC_i} \in \mathbb{SO}(3)$ [20]. Fig. 5 depicts a contact point C_i located at the thumb and its orientation

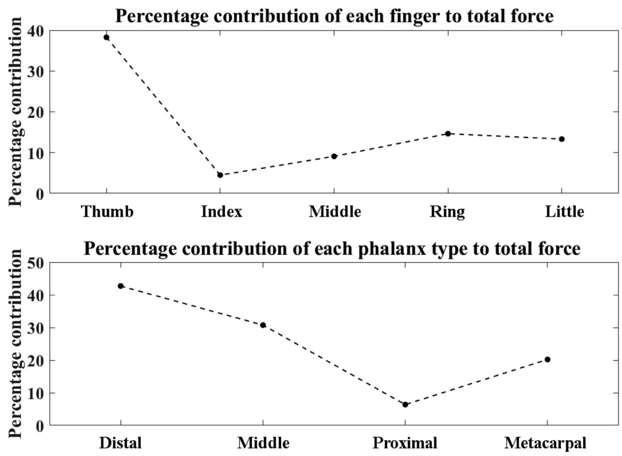

Fig. 6. TOP: Contribution of each finger to total normal force. BOTTOM: Distribution of the force along the phalanxes.

with respect to the device's center O. While the z axis at every contact point was normal to the surface of the phalanx, the y axis was oriented vertically upwards (i.e., opposite to the direction of gravity). In total, nineteen contact points were established, with a contact point at every phalanx. The wrench acting at each contact point C_i is given by $f_{C_i} = [f_{x_i}\ f_{y_i}\ f_{z_i}\ \tau_{z_i}]^T \in \mathbb{R}^4$. The first three components are forces acting along the coordinates axes at contact point C_i, while the last component is the torque acting about the z axis of contact point C_i. The position vectors and rotation matrices of all contact points are stacked element-wise to form a grasp map $G : \mathbb{R}^{76} \rightarrow \mathbb{R}^6, G(f_C) \mapsto F_O$, i.e., maps the wrenches at each C_i to O. Assuming that the device weighs 5.253 N and generates a torque of 0.7 Nm, the wrench F_O is given by $\begin{bmatrix} 0 & -5.253 & 0 & 0.7 & 0 & 0.7 \end{bmatrix}^T$, where the first and last three elements represents the force and torque respectively acting at O about the x, y, and z axis. For a given wrench F_O generated by the device, it is desired that the cumulative forces acting on the hand (i.e., f_C) be minimized, while satisfying the constraints to avoid slippage [21]. This can be formulated as the following optimization problem [20].

$$\underset{f_{C_i}}{\text{minimize}} \quad f_C^T f_C \tag{1}$$

$$\text{subject to} \quad G f_C = F_O \tag{2}$$

$$f_{x_i}^2 + f_{y_i}^2 \leq (\mu f_{z_i})^2, \qquad \text{for } i = 1, \ldots, 19 \tag{3}$$

$$\tau_{z_i}^2 \leq (\gamma f_{z_i})^2, \qquad \text{for } i = 1, \ldots, 19 \tag{4}$$

$$-f_{z_i} \leq 0, \qquad \text{for } i = 1, \ldots, 19 \tag{5}$$

where μ is the static friction coefficient and γ is the torsional friction coefficient. For the sake of simplicity, both coefficients are chosen as 0.47, which is the friction coefficient between human skin and Nylon as per [22]. Constraint (2) enforces f_C mapping to F_0. Constraint (3) and (4) ensure the forces/torque at each contact point do not exceed the associated sticking friction component. Lastly, (5) makes the normal force point into the hand at each contact point.

The results revealed that the normal components of each wrench f_{C_i} was greater than all other components. The total normal force acting on the hand was estimated to be 12.62 N. The percentage contribution of the cumulative normal forces, acting on each finger, towards the total normal force has been reported in Fig. 6. It was observed that, among all fingers, the thumb was subjected to 38% of the overall load. Further, it was found that the distal phalanges would be subjected to most of the normal force. Note that the thumb contributed the most since the thumb is the only opposing digit against the other four digits while holding the *Gymball*. These results are in agreement with the trends reports in [16], [17]. Hence the designed grooves made *Gymball* easy-to-grip with a cylindrical hold (N8).

V. Feasibility Study

A primary assessment of the *Gymball* can be made by answering the following questions: (i) can the produced torque cause the user's hand to move about the wrist? (ii) can the magnitude of the generated hand motion be modulated? (iii) can we control the frequency of hand oscillations? These questions address needs (N1) and (N2). We conducted a study with two healthy subjects (1 female, 1 male, both 28 years old). The subjects were asked to relax the hand while exerting minimal effort to hold *Gymball*. The forearm of the subjects was supported against a table-top. We independently varied the rotational speed of the rotor and gimbal. We tested four rotor speeds: 900, 1350, 1800, 2250 rpm, during which the gimbal speed was 200 rpm. We also tested four gimbal speeds: 66, 110, 200, 290 rpm, during which the rotor speed was 1800 rpm. Two 30 s trials were conducted for each working condition. Based on the proof-of-concept and simulation tests, it is known that the generated hand motion under constant rotor and gimbal speed, the would be oscillatory. We thus chose two metrics: (i) Range-of-motion which is the average peak-to-peak angular displacements about the axes x_0 and z_0 (specified in Fig. 5), (ii) Frequency of hand oscillation determined using a Fast Fourier Transform of the IMU signals. Both metrics ignore rigid-body motion (bias) of the subjects' hand.

VI. Results and Discussion

During each trial, consistent oscillations were observed about each axis. Refer to the the Supplemental document for an example trial depicting said oscillations. Fig. 7 presents the averaged results across trials. A maximum of 4.0 degrees and 7.0 degrees of hand motion was observed in Subject 1 (Male) and Subject 2 (Female), respectively. Within each trial, the frequency of hand motion about both axes was found to be the same. Further, Subject 2 experienced larger oscillations about axis x_0 than z_0, contrary to the oscillations experienced by Subject 1. Increasing the rotor speed increased the range-of-motion in both subjects, but didn't affect the frequency. Increasing the gimbal speed, however, increased both range-of-motion and frequency. We also note that the frequency of hand oscillations closely matches the gimbal's rotational frequency. For example, when the gimbal speed was 200 rpm (=3.33 Hz), the hand motion's frequency was between 3.17 Hz to 3.31 Hz for both subjects.

The generated consistent and passive oscillatory motion is highly applicable to occupational therapies and haptic feedback (N1)–the first indication that *Gymball* is suited to hand rehabilitation and haptics. The difference in oscillation amplitudes across subjects could be related to the differences between the subjects' hand inertia and wrist joint impedance. Going forward, we wish to determine the relationship, if any, between range-of-motion and joint impedance. Studies have linked a joint's health with the joint's impedance [23]. If the relationship between the range-of-motion and joint impedance does exist, therapists/clinicians can then use the relationship to monitor a patient's rehabilitation progress.

The above results show that we can control the nature of hand motion generated using *Gymball* (N2). We can fix the frequency of hand oscillations using the gimbal speed, and then fine-tune the range-of-motion using the rotor speed. But to control the motion's amplitude about each axis (x_0 and z_0), we would need an user-specific relationship between the rotor and gimbal speeds to the hand motion's amplitude. A simple calibration routine would help determine this vital relationship. With this in mind, we wish to explore

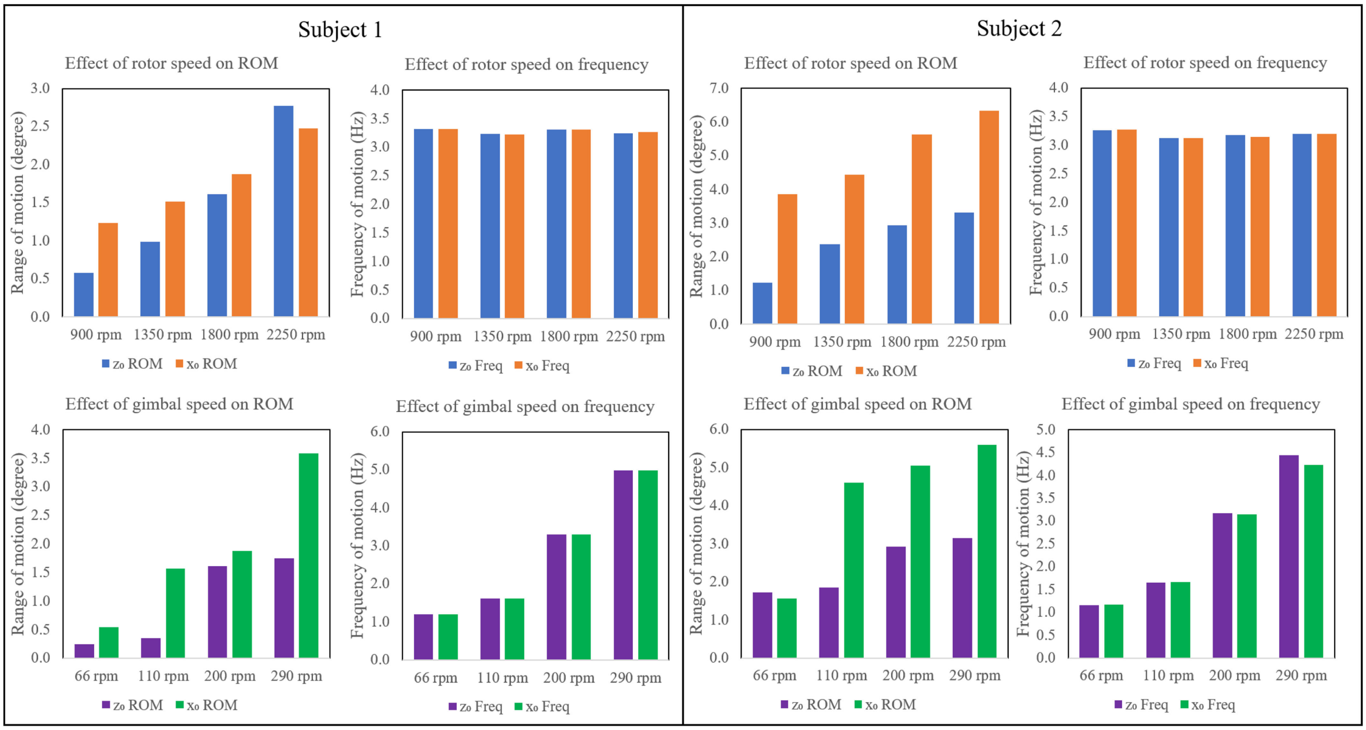

Fig. 7. Range-of-motion (ROM) about x_0 and z_0 axes and the corresponding frequency for both subjects. TOP: Effect of rotor speed. BOTTOM: Effect of gimbal speed.

designing different patterns of hand motion catered to different hand rehabilitation therapies or haptic feedback information.

VII. Limitations and Future Work

Currently, the maximum gimbal speed was limited to 290 rpm. However, the device is capable of 400 rpm, which would result in higher range-of-motion. The imposed speed limitation was due to the wide circumference of the device–making it hard to grip at higher speeds. Another limitation of *Gymball* is that both the gimbal and rotor do not have encoders for angular velocity information. Future designs will aim to develop a custom solution that includes hall effect sensors for feedback control. Additionally, the sample size is also small for this study. Going forward, we will investigate the user-specific relationship between the input rotor-gimbal speed and the generated hand motion's amplitude. To do so, we will conduct a large sample-sized study and determine a torque model. With the help of occupational therapists, we will design therapy specific hand motions. For haptics, we will conducts a study to determine how accurately users can identify the torque based feedback signals from *Gymball*.

VIII. Conclusion

We proposed a novel gyroscopic device for haptics and hand rehabilitation, *Gymball*. The device is an improvement over the state-of-the-art since it employs a symmetric design to mitigate unnecessary vibrations, has a larger rotor and gimbal range-of-motion due to a slip-ring assembly, and has greater user appeal. A theoretical analysis of the grip deemed the forces imposed on the hand to be within the norms for a cylindrical grip, making the design ergonomic. The torque generated by the device (estimated to be 0.5 Nm) is strong enough to cause the user's hand to move about the wrist in an oscillatory fashion at constant rotor and gimbal speed. While the amplitude of hand motion (for a given rotor and gimbal speed) varies from person to person, the frequency of the oscillation is determined by the gimbal's rotational speed. With an appropriate calibration routine, we can determine the mapping between the rotor-gimbal speeds to hand motion amplitude and generate different motion patterns.

References

[1] O. Schneider, K. MacLean, C. Swindells, and K. Booth, "Haptic experience design: What hapticians do and where they need help," *Int. J. Hum.-Comput. Stud.*, vol. 107, pp. 5–21, 2017.

[2] L. M. Kuchinke and B. Bender, "Technical view on requirements for future development of hand-held rehabilitation devices," in *Proc. IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics*, 2016, pp. 804–809.

[3] Y.-T. Pan, H. U. Yoon, and P. Hur, "A portable sensory augmentation device for balance rehabilitation using fingertip skin stretch feedback," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 1, pp. 31–39, Jan. 2017.

[4] H. U. Yoon, N. Anil Kumar, and P. Hur, "Synergistic effects on the elderly people's motor control by wearable skin-stretch device combined with haptic joystick," *Front. Neurorobot.*, vol. 11, 2017, Art. no. 31.

[5] GyroGear, "GyroGlove," [Online]. Available: http://gyrogear.co/gyroglove

[6] K. N. Winfree, J. Gewirtz, T. Mather, J. Fiene, and K. J. Kuchenbecker, "A high fidelity ungrounded torque feedback device: The iTorqU 2.0," in *Proc. 3rd Joint EuroHaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2009, pp. 261–266.

[7] J. M. Walker, A. M. Okamura, and M. J. Kochenderfer, "Gaussian process dynamic programming for optimizing ungrounded haptic guidance," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2018, pp. 8758–8764.

[8] A. Badshah, S. Gupta, D. Morris, S. N. Patel, and D. Tan, "GyroTab: A handheld device that provides reactive torque feedback," in *Proc. CHI Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, 2012, pp. 3153–3156.

[9] D. K. Zondervan *et al.*, "Home-based hand rehabilitation after chronic stroke: Randomized, controlled single-blind trial comparing the MusicGlove with a conventional exercise program," *J. Rehabil. Res. Develop.*, vol. 53, no. 4, pp. 457–472, 2016.

[10] D. Cruz, M. L. G. Emmel, M. G. Manzini, and P. V. Braga Mendes, "Assistive technology accessibility and abandonment: Challenges for occupational therapists," *Open J. Occup. Ther.*, vol. 4, no. 1, 2016, Art. no. 10.

[11] G. Saposnik *et al.*, "Effectiveness of virtual reality using Wii gaming technology in stroke rehabilitation: A pilot randomized clinical trial and proof of principle," *Stroke*, vol. 41, no. 7, pp. 1477–1484, 2010.

[12] N. Smania *et al.*, "Rehabilitation procedures in the management of spasticity," *Eur. J. Phys. Rehabil. Med.*, vol. 46, no. 3, pp. 423–438, 2010.
[13] G. Sequeira, J. W. Keogh, and J. J. Kavanagh, "Resistance training can improve fine manual dexterity in essential tremor patients: A preliminary study," *Arch. Phys. Med. Rehabil.*, vol. 93, no. 8, pp. 1466–1468, 2012.
[14] O. Lambercy, L. Dovat, R. Gassert, E. Burdet, C. L. Teo, and T. Milner, "A haptic knob for rehabilitation of hand function," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 1, pp. 356–366, Sep. 2007.
[15] Shapeways, "3D printing materials," [Online]. Available: https://www.shapeways.com/materials
[16] A. A. Amis, "Variation of finger forces in maximal isometric grasp tests on a range of cylinder diameters," *J. Biomed. Eng.*, vol. 9, no. 4, pp. 313–320, 1987.
[17] L. R. Enders, "Role of sensation in altered phalanx grip force in persons with stroke," Ph.D. dissertation, Univ. Wisconsin Milwaukee, 2014.
[18] P. Hur, B. Motawar, and N. J. Seo, "Hand breakaway strength model – effects of glove use and handle shapes on a person's hand strength to hold onto handles to prevent fall from elevation," *J. Biomech.*, vol. 45, no. 6, pp. 958–964, 2012.
[19] J. Schmit, "Human left hand - 3D CAD model - GrabCAD," [Online]. Available: https://grabcad.com/library/human-left-hand
[20] R. M. Murray, Z. Li, and S. S. Sastry, *A Mathematical Introduction to Robotic Manipulation*, Boca Raton, FL, USA: CRC Press, 1994.
[21] R. Tomovic, G. Bekey, and W. Karplus, "A strategy for grasp synthesis with multifingered robot hands," in *Proc. IEEE Int. Conf. Robot. Automat.*, 1987, vol. 4, pp. 83–89.
[22] M. Zhang and A. F. T. Mak, "In vivo friction properties of human skin," *Prosthetics Orthotics Int.*, vol. 23, pp. 135–141, 1999.
[23] J. Given, J. Dewald, and W. Rymer, "Joint dependent passive stiffness in paretic and contralateral limbs of spastic patients with hemiparetic stroke," *J. Neurol., Neurosurgery, Psychiatry*, vol. 59, pp. 271–279, 1995.