GyroVR: Simulating Inertia in Virtual Reality using Head Worn Flywheels

Jan Gugenheimer
Ulm University
Ulm, Germany
jan.gugenheimer@uni-ulm.de

Dennis Wolf
Ulm University
Ulm, Germany
dennis.wolf@uni-ulm.de

Eythor R. Eiriksson
DTU Compute
Kgs. Lyngby, Denmark
eruei@dtu.dk

Pattie Maes
MIT Media Lab
Cambridge, MA
pattie@media.mit.edu

Enrico Rukzio
Ulm University
Ulm, Germany
enrico.rukzio@uni-ulm.de

ABSTRACT
We present GyroVR, head worn flywheels designed to render inertia in Virtual Reality (VR). Motions such as flying, diving or floating in outer space generate kinesthetic forces onto our body which impede movement and are currently not represented in VR. We simulate those kinesthetic forces by attaching flywheels to the users head, leveraging the gyroscopic effect of resistance when changing the spinning axis of rotation. GyroVR is an ungrounded, wireless and self contained device allowing the user to freely move inside the virtual environment. The generic shape allows to attach it to different positions on the users body. We evaluated the impact of GyroVR onto different mounting positions on the head (back and front) in terms of immersion, enjoyment and simulator sickness. Our results show, that attaching GyroVR onto the users head (front of the Head Mounted Display (HMD)) resulted in the highest level of immersion and enjoyment and therefore can be built into future VR HMDs, enabling kinesthetic forces in VR.

Author Keywords
gyroVR; haptics; virtual reality; mobile VR, nomadic VR

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

INTRODUCTION
Virtual Reality HMDs strive to immerse the user inside a virtual environment and are currently mainly targeting the visual sense. Several research projects showed that including the haptic sense inside a virtual environment leads to an increased level of immersion [17].

GyroVR focuses on the kinesthetic part of the haptic perception and mainly on inertia, which occurs when being in fast motion (e.g. flying) or in an altered environment (e.g. underwater). The resistance of the wind, when flying in a wingsuit acts upon the human body as a kinesthetic force, which impedes the movements of the head or limbs similar to when people try to move underwater. This concept of motion is currently one of the most used for Oculus Rift experiences.

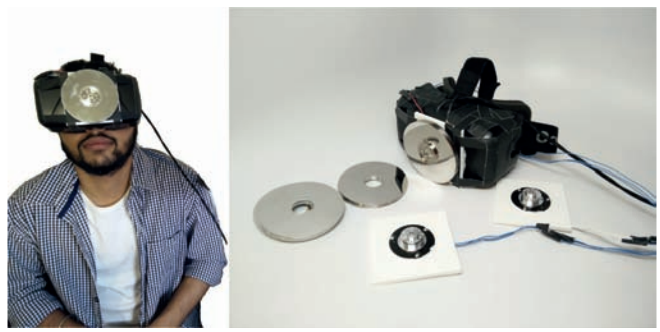

Figure 1. Left: A user wearing a VR HMD with GyroVR attached. Right: A prototype implementation of GyroVR attaching flywheels on the front of an Oculus Rift DK2.

We enable this sensation by attaching flywheels to the human head. These flywheels leverage the gyroscopic effect which occurs when the user tries to rotate his head against the rotational axis of the spinning flywheel. The gyroscopic effect will affect the motion of the users to the perpendicular axis of the motion which is mainly perceived as a resistance [19]. In combination with the visuals of the virtual scene the sensation of inertia is created. We conducted a user study (n=12) to explore how mounting GyroVR to different positions on the human head (back and front) impacts the level of immersion, enjoyment and simulator sickness inside a virtual environment.

Contributions
The main contributions of this work are: (1) the concept of simulating kinesthetic motion forces using head worn flywheels,(2) the implementation of GyroVR, a small, self containing and generic device capable of being attached to the human body, (3) the insights from our study on human perception and the impact of

UIST 2016, October 16–19, 2016, Tokyo, Japan.

DOI: http://dx.doi.org/10.1145/2984511.2984535

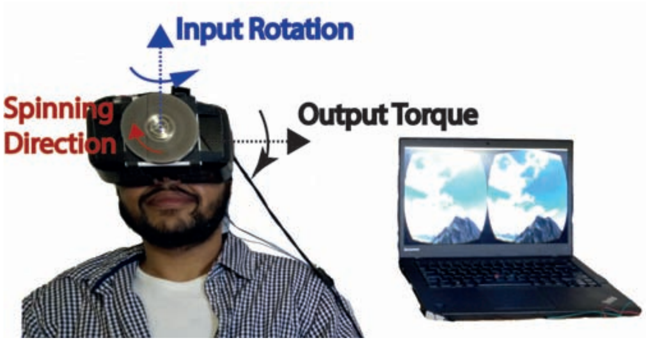

Figure 2. GyroVR is designed to render the simulated force of inertia occurring during movements. The key idea is that the flywheel mounted on the VR HMD impedes the motion of the users. Here the user is experiencing a flying simulation and tries to steer his direction using his head motion (Users' Motion). The rotation speed of GyroVR is correlated with the speed the user has in the virtual environment. GyroVR impedes this motion by generating a perpendicular force creating an experience for the user where it is more difficult to move his head when he is in high motion.

kinesthetic forces by head worn flywheels attached to different locations in terms of immersion, enjoyment and simulator sickness.

GYROVR

GyroVR is designed as an ungrounded haptic feedback device to simulate the kinesthetic force of inertia which fits to different VR experiences (e.g. flying). Ungrounded means that GyroVR has no grounding to counterbalance the output force such as Phantom or HapticMaster [13]. Figure 2 illustrates a setup where the user flies through an environment and depending on his speed perceives a higher or lower level of resistance during his head movements. The concept of GyroVR leverages the effect that the directional force is not perceived precisely enough and more like a general resistance [18]. One important concept of GyroVR is that the force generated does not necessarily have to be realistic (e.g. actual wind resistance). In informal pre-evaluation with colleagues we found that users mostly do not know the exact force which should be acting upon them in most situations but only expect some kind of force which is comprehensible.

Implementation

Similar to [3] we built GyroVR out of desktop computer hard drive components (Western Digital WD 2500). We removed the motor (7200 rpm overclocked to ≈12.000 rpm) and discs from the HDD. For our implementation we used three discs on each motor resulting in a total weight of 96g. We experimented with a different number of discs and found a balance between weight and performance using three. Furthermore, a higher number of discs resulted in the motors to struggle at start-up since they are not used to spin a higher number of discs. To control the three phase HDD motor we used a Hobbyking 30A ESC which receives a PWM signal from an Arduino Nano. After our initial tethered prototype with three motors on the HMD (Figure 6) we built a mobile version (Figure 3) by adding the Bluetooth HC-06 module for the communication between computer and Arduino and adding a 1500mAh Lipo-Battery (from an AR Drone 2.0). The use of off the shelf hardware allows researchers to easily rebuild our implementation.

To experiment with the force on different locations of the human body we built a mobile version (Figure 3 right) where we

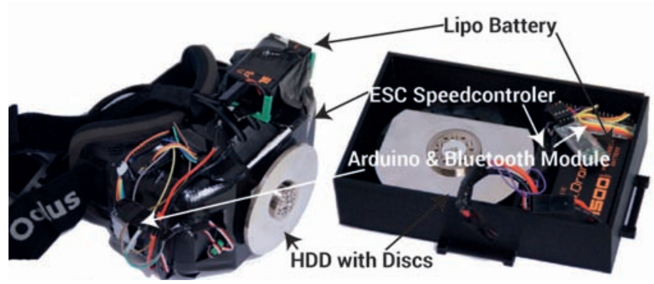

Figure 3. Two implementations of GyroVR. Left: The GyroVR prototype directly attached onto an Oculus Rift DK2. Right: A mobile implementation of GyroVR, built in a generic form factor to be mounted onto the human body.

assembled all components inside a 3D printed case (overall weight 390g). This prototype can be mounted onto the human body using straps (Figure 5). To reduce some of the weight we built a second prototype where we assembled all the components directly onto an Oculus Rift DK2 (Figure 3 left).

Gyroscopic Precession

The force generated by GyroVR is based on Newton's first law of motion which states that objects in motion try to stay in motion. The rotational pendant to this is the gyro effect which states that spinning masses will continue spinning in the same direction around the same axis. Once the user rotates his/her head at a desired angular velocity ω_{in}, a gyroscopic torque $\tau_o ut$ is experienced perpendicular to the head rotation axis. (Figure 4). The relationship is as follows

$$\tau_{out} = \omega_{in} \times L_s = \omega_{in} \times I\omega_s \qquad (1)$$

where L_s is the spin angular momentum, I is the moment of inertia and ω_s is the angular velocity of the spinning mass.

By having a double gyroscope setup, sharing the same rotational axis and spinning in the same direction, the angular momentum contribution becomes additive. Effectively doubling the perceived effect and output torque τ_{out}. Figure 4 depicts such a double gyroscope setup where the gyroscopes have been mounted in such a way that they provide a counter balance of weight. Additionally, it illustrates the relationship between head rotation velocity ω_{in} and the gyroscopic torque τ_{out} experienced by the user around the yaw axis.

Mounting Positions

We experimented with several mounting position on the users body using the GyroVR mobile prototype (Figure 5). Our goal was to find mounting positions where users would perceive the force strong enough so it could be used in a user study. Since the force of GyroVR is a reactive force (only perceived if an input force is generated e.g. rotating the head) we experimented with mountings on the human body which are used frequently in motion when inside a virtual environment. The evaluation of the different mounting positions we report here are based on informal pre-evaluations the authors conducted on themselves to pre-select relevant mounting positions for the follow up user study. We evaluated the mounting positions based on *ease of attachment and level of perception*.

Hands: Mounting the device onto the palm (or holding it in the hand) resulted in the strongest perception of the force. This is

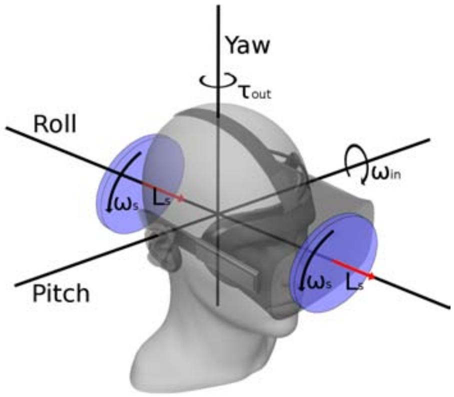

Figure 4. When disks are spun with angular velocity ω_s and the head is rotated around an input axis at angular velocity ω_{in}, the gyroscopic output torque τ_{out} around the yaw axis is experienced by the user.

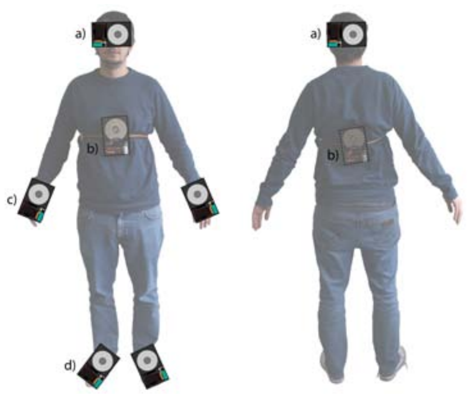

Figure 5. The different mounting positions on the human body which were explored with the mobile implementation of GyroVR.

probably because of the high density of muscle spindles which are responsible for perceiving the kinesthetic force [8]. The mounting onto the hand turned out to be more difficult since the prototype must be rigidly attached and thereby restricted motions of the hand. Furthermore, the size of the prototype lead to occlusion of the fingers which excluded simple hand tracking using the Leap Motion. The best result occurred from holding the prototype in the hand. We excluded that option of holding, since similar results were already reported in prior work [3, 21].

Torso: The least force was perceived when GyroVR was mounted on the torso. We experimented with different mounting locations but did not find a position which resulted in a force which could actually be perceived. As the torsos freedom of motion is by rotating around a vertical axis, the GyroVR must exert an output torque by twisting around the horizontal axis, essentially leveraging the entire body.

Legs/Feet: Attaching GyroVR to the legs resulted similar to the torso location in an easy mounting but low perception of the output force. We also experimented with mounting GyroVR to the feet (similar to a shoe). The force is only perceived when tilting the foot and is only of relevance for room scale VR such as HTC Vive.

Head: Mounting GyroVR onto the head resulted in a high perception of the force since the neck consists of most muscle spindles

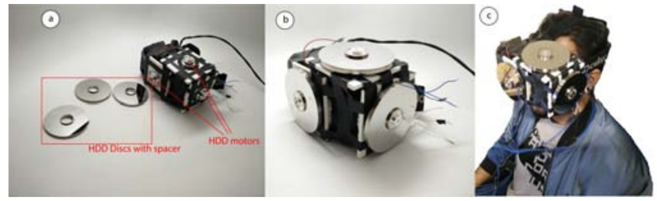

Figure 6. An early prototype of GyroVR on an Oculus Rift DK2 (a) which had a flywheel mounted onto each axis (b). We conducted informal evaluations to asses the output force (c)

[8]. We built one initial prototype (Figure 6) with flywheels on each rotational axis (yaw, pitch and roll). We then experimented with each individual flywheel and its possible combination and ended up with mounting the flywheel to the roll axis as the best result. The reason is that when mounted on the roll axis the gyroscopic effect is perceived when applying a force on the yaw and pitch axis (basically turning the head left/right or up/down). This position benefits from the fact that users explore the virtual environment by rotating the head. Even if the realistic case would be to perceive the force on the whole body, by bundling this haptic feedback with the main source of input (head rotation) the user gets an immediate feedback for an action and accepts the force as part of the immersive experience (see section user study).

APPLICATION EXAMPLES

To explore the design space for GyroVR we implemented three example applications which each create a different mapping of the force and the environment (Figure 7). We used those applications for the user study. For some applications we needed to let the participants generate input (e.g. press button to fly). We used a wireless bluetooth gamepad for this interaction. Applications which depend on virtual forward motion tend to induce simulator sickness (sensory conflict theory). Due to the nature of inertia which mostly appears during motion we took some precautions (e.g. Oculus Guidelines) during the application design to lower simulator sickness. In every scenario we used a different mapping between the virtual environment and the physical rotation to dynamically control the rpm. To generally shorten the ramp up time the flywheels are kept constantly spinning on low rpm (which did not generate enough torque for the participants to feel). All applications were implemented using Unity 3D.

Simulating Forces of Motion - Flying

In the flying game (Figure 7 a) the user can fly over a city. By holding down one button on the gamepad the user can speed up and control his direction by rotating the head. The rotational speed of the flywheel is mapped onto the virtual speed inside the game. For the flying game we used a linear mapping between virtual movement and rotation speed. This allows the user to perceive a higher resistance in turning his head when flying in higher speed. To encourage head rotation we placed stars inside the environment which the user has to collect. The placement is done in such a way that after collecting one star the users has to quickly rotate towards the next target.

Impeded Motion - 3D Shooter

Figure 7 b shows the implementation of the 3D shooter game. The user is located inside a warehouse and has to find two

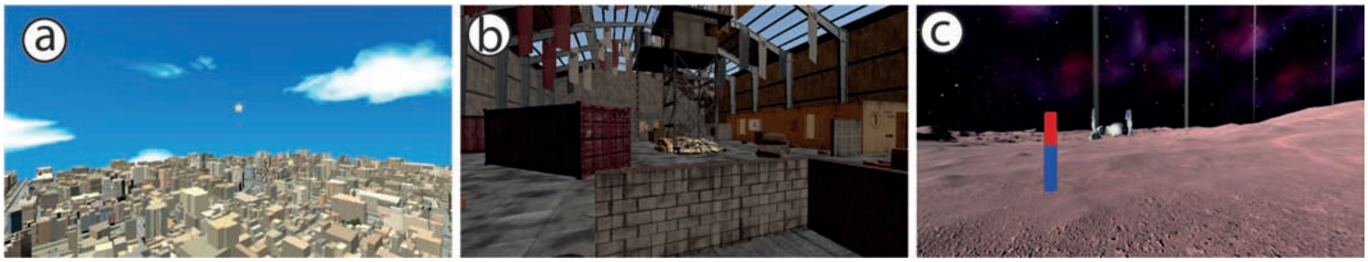

Figure 7. Screenshots of the applications which users experienced in the user study. (a) The flying application showing a star in the distance. (b) A first person view of the warehouse from the 3D Shooter game. (c) The surface of the foreign planet showing the location of several parts which the user has to collect

weapons hidden in random locations. The controls work by having one button to run and a second one to jump. The direction of the running is controlled via head rotation. During the search the users get constantly shot by hidden enemies which they can't find. The more damage the user takes the faster the flywheel spins and the more difficult it becomes to move. At the start of the scene no rotation was used. Every time a user gets hit, the rpm are increased rapidly by a 6th of the maximum rpm. After seven hits the game ends. This allows the user to experience an impeded motion as if he is wounded.

Simulating new Environments - Space Jumper

The last game (Figure 7 c) locates the user on a new planet with new physical forces. The flywheel is constantly spinning at full speed thereby highly restricting head motion and simulating a new form of gravitation. The get off the planet the user has to collect three parts which he needs to repair his spaceship. To move on the planet users are encouraged to jump. To encourage a high head movement, users only have a certain "boost" which they can use to jump that has to be regenerated by shaking their head. The gravitation on the planet is set to almost zero. The user has visually the impression as if he moves in lower gravity, the flywheels generate a force as if he would actually be in an environment with a higher gravitation as earth (since moving the head is difficult). This application beautifully demonstrates the concept of non-realistic forces. Even if that scenario is physically impossible, participants inside our user study ignored this fact and perceived the forces as appropriate, some even calling it "realistic".

RELATED WORK

Our work builds upon the work in the field of ungrounded kinesthetic feedback and virtual reality.

The gyroscopic effect was often used to create an ungrounded kinesthetic force such as the GyroCube [19] which is a handheld gyroscope generating forces along each rotational axis. Sakai et al. evaluated the levels of perception inside the users palm using GyroCube [18]. Badshah et al. applied this concept into the field of HCI by attaching flywheels onto the back of a tablet to generate kinesthetic forces for the user [3]. Several authors presented a concept to make the gyroscopic effect proactive by attaching a flywheel onto a gimbal and control that gimbal [21, 2, 22] to give the user directional cues. Murer et al. presented this concept attached onto a tablet called "TorqueScreen" [16]. By rotating the gimbal with a flywheel attached, the authors could generate kinesthetic feedback allowing the user to feel a virtual ball on the tablet bounce of the edges. The main difference to GyroVR is that all those prototypes were designed to be handheld and not mounted onto the human body.

Figure 8. The study apparatus of GyroVR consisting of a Oculus Rift DK2 with GyroVR attached and a bicycle helmet having a mobile GyroVR prototype attached to the back.

A different direction in the field of ungrounded kinesthetic feedback is work which tries to mount those flywheels onto the human body. Mostly the motivation is to assist human balance [1, 4, 14]. Those prototypes are often quite large to generate a strong enough force and too heavy for casual use. Ando et al. presented a concept for a body worn prototype based on brake change in angular momentum to create a directional force [1]. The prototype built, however, was not wearable but users had to hold it in their hand.

In the field of Virtual Reality, there is a big direction of work focusing on novel input concepts [5] and generating haptic feedback [11, 7, 12, 17, 6]. Early prototypes were used in CAVE environment and were attached to the users limbs using exoskeletons [20] or pulley systems [15]. Both systems are considered to use a grounded force. Recently, Lopes et al. presented a concept for simulating impact in VR using electrical muscular stimulation and a solenoid [11].

To our best knowledge, GyroVR is the first to use head-worn flywheels to simulate kinesthetic feedback in VR.

USER STUDY

To measure the impact of GyroVR onto immersion, engagement, enjoyment and simulator sickness we conducted a user study (n=12). We also evaluated the best position of GyroVR on the users head.

Study Design and Procedure

The study had one independent variable *motor location* with four levels (front, back, both and none). In the *both* condition both flywheels rotated in the same direction along the roll axis to sum up the force. For the user study we used a different apparatus (Figure 8) which consisted of a bicycle helmet which had a GyroVR prototype mounted on it. We used the helmet to ensure

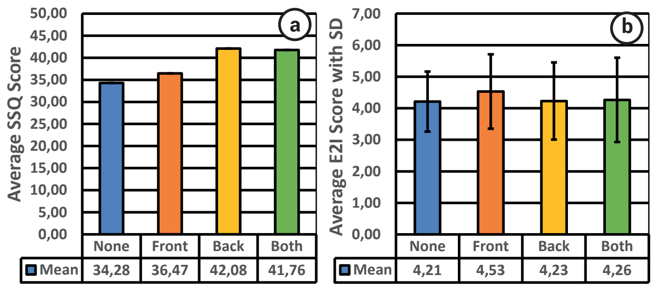

Figure 9. A distribution of the simulator sickness (a) and immersion, engagement and enjoyment questionnaire (b) of the user study.

a sturdy attachment of GyroVR onto the back of the participants' head. To ensure that the force was created equally, both flywheels were equidistant to the users head (≈ 8cm). The *none* condition was used as the baseline. The study took on average 30 minutes and participants received 5 currency. The flywheels generate a small rotation noise which was not heard by the participants due to the use of headphones. To avoid vibration we used hand moldable plastic to press fit a perfectly fitting layer of plastic between the HMD case and the flywheel mount. The battery lasted for at least 2 studies (1h) before charging.

Participants were introduced to the concept of GyroVR and could experience the force. Afterwards they put on the Oculus DK2 and the bicycle helmet and played all three applications (section *Application Examples*) with each of the four conditions of the motor (front, back, both and none). After each motor condition participants were asked to fill out the SSQ (Simulator Sickness Questionnaire) [9] and E^2I questionnaire (immersion, engagement and enjoyment) [10]. At the end participants rated all four conditions as what they perceived as the best experience. Applications and motor conditions were counterbalanced using a Latin-square.

Participants
We randomly recruited 12 participants (3 female) with an average age of 28.5 (range: 25 to 36) from our institution. Six participants had already experience with VR HMDs and all had an academic background.

Results
Quantitative: Figure 9 a shows the distribution of the simulator sickness of all levels of the motor condition. A repeated measures ANOVA revealed no significant differences (F(3,33)=.639, n.s.). Even if not significant, the trend shows that the front mount resulted in the lowest level of simulator sickness compared to the other motor levels. Participants in general mentioned that the applications induced a higher level of simulator sickness since they all dependent on virtual movement. The overall ranking of immersion, engagement and enjoyment over all motor levels can be found in Figure 9 b. A repeated measures ANOVA revealed no significant differences (F(3,33)=.745, n.s.) between the levels. Nevertheless, the front condition received a slightly higher ranking. This again correlates with the user feedback we received during the study.

Qualitative: In the final feedback after the user study participants comments can be categorized in three topics (*immersion*, *sickness*, *fatigue*): Rapid increase of RPM resulted in a little nudge in a direction and was partially perceived as 'unpleasant' and therefore fitting to increase the level of *immersion* of the 3D Shooter, where a hit from a bullet was simulated by a rapid increase of rpm. Participants said they perceived the front condition as being the strongest in terms of output force. In the final rating of the overall best experience participants preferred having a motor (7) vs having no motor (5). The participants which ranked the "no motor" condition the best mostly experienced an overall high level of *simulator sickness*, which they then correlated with the motor running. In a final ranking participants (6) reported that during the motor conditions, using both motors induced the most level of sickness. Participant 7 mentioned that if GyroVR was not tightly fixed to the head this potentially increased the sickness. High rpm were reported to potentially lead to less head movement due to *fatigue*. Participant 9 suggested to use this effect as a 'punishment' in an attention guidance scenarios. The overall weight of the study apparatus resulted in a certain level of fatigue over the duration of the whole study. However, removing one of the gyros would result in an unbalanced setup (and create an unfair comparison between conditions). Therefore, we decided the leave both gyros on the participants during the whole study. A possible solution to keep the same output force but reducing the weight would be by increasing the rpm. A future prototype which is based around a custom motor with higher rpm would be able to generate the same output force but avoid the high weight and resulting fatigue effects.

DISCUSSION
Our study showed that GyroVR creates an "immersive and realistic" (P3, P5) kinesthetic force which "enhances the experience" (P9). After experiencing a condition with either of the motors and afterwards the *none* condition, participants reported the experience to be "boring without the force" (P10). Overall participants reported they enjoyed the concept despite a certain base level of simulator sickness. Even though the user study did not quantitative show a clear benefit for immersion, engagement and enjoyment when using GyroVR, a possible trend does exist, which warrants further testing with a larger sample size to determine if the trend truly indicates significance.

CONCLUSION
We presented GyroVR, head worn flywheels designed to render inertia in Virtual Reality. These flywheels leverage the gyroscopic effect which impedes users head movement and thereby is perceived as inertia. We presented several implementations and initially explored the mounting positions on the human body. In three example applications we explore the design space and different concept of mapping the force inside of the virtual environment. In a user study we explored the effect of GyroVR attached to the users head on immersion, engagement, enjoyment and simulator sickness. Our results give a first understanding of the implications of attaching a flywheel to the front of a HMD to enable kinesthetic forces of inertia in virtual reality.

ACKNOWLEDGMENTS
We thank whole Fluid Interfaces group at the Media Lab and in particular Tal Achituv for the technical advise. This work was conducted within SFB/TRR 62 Companion-Technology for Cognitive Technical Systems and the Emmy Noether research group Mobile Interaction with Pervasive User Interface both funded by the German Research Foundation (DFG).

REFERENCES

1. Ando, H., Obana, K., Sugimoto, M., and Maeda, T. A wearable force display based on brake change in angular momentum. *Proc Artificial Reality and Telexistence 2002* (2002), 16–21.

2. Antolini, M., Bordegoni, M., and Cugini, U. A haptic direction indicator using the gyro effect. In *World Haptics Conference (WHC), 2011 IEEE*, IEEE (2011), 251–256.

3. Badshah, A., Gupta, S., Morris, D., Patel, S., and Tan, D. Gyrotab: A handheld device that provides reactive torque feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '12, ACM (New York, NY, USA, 2012), 3153–3156.

4. Chiu, J., and Goswami, A. Design of a wearable scissored-pair control moment gyroscope (sp-cmg) for human balance assist. In *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers (2014), V05AT08A023–V05AT08A023.

5. Gugenheimer, J., Dobbelstein, D., Winkler, C., Hass, G., and Rukzio, E. Facetouch: Enabling touch interaction in display fixed uis for mobile virtual reality. In *Conditionally Accepted UIST '16*, UIST '16, ACM (2016).

6. Gugenheimer, J., Wolf, D., Haas, G., Krebs, S., and Rukzio, E. Swivrchair: A motorized swivel chair to nudge users' orientation for 360 degree storytelling in virtual reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, ACM (New York, NY, USA, 2016), 1996–2000.

7. Hirose, M., Hirota, K., Ogi, T., Yano, H., Kakehi, N., Saito, M., and Nakashige, M. Hapticgear: the development of a wearable force display system for immersive projection displays. In *Virtual Reality, 2001. Proceedings. IEEE*, IEEE (2001), 123–129.

8. Jones, L. A. Kinesthetic sensing. In *in Human and Machine Haptics*, Citeseer (2000).

9. Kennedy, R. S., Lane, N. E., Berbaum, K. S., and Lilienthal, M. G. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology 3*, 3 (1993), 203–220.

10. Lin, J. J.-W., Duh, H. B., Parker, D. E., Abi-Rached, H., and Furness, T. A. Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In *Virtual Reality, 2002. Proceedings. IEEE*, IEEE (2002), 164–171.

11. Lopes, P., Ion, A., and Baudisch, P. Impacto: Simulating physical impact by combining tactile stimulation with electrical muscle stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, UIST '15, ACM (New York, NY, USA, 2015), 11–19.

12. Maeda, T., Ando, H., Amemiya, T., Nagaya, N., Sugimoto, M., and Inami, M. Shaking the world: galvanic vestibular stimulation as a novel sensation interface. In *ACM SIGGRAPH 2005 Emerging technologies*, ACM (2005), 17.

13. Massie, T. H., and Salisbury, J. K. The phantom haptic interface: A device for probing virtual objects. In *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*, vol. 55, Chicago, IL (1994), 295–300.

14. Matsuzaki, R., and Fujimoto, Y. Walking assist device using control moment gyroscopes. In *Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE*, IEEE (2013), 6581–6586.

15. Murayama, J., Bougrila, L., Luo, Y., Akahane, K., Hasegawa, S., Hirsbrunner, B., and Sato, M. Spidar g&g: a two-handed haptic interface for bimanual vr interaction. In *Proceedings of EuroHaptics* (2004), 138–146.

16. Murer, M., Maurer, B., Huber, H., Aslan, I., and Tscheligi, M. Torquescreen: Actuated flywheels for ungrounded kinaesthetic feedback in handheld devices. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '15, ACM (New York, NY, USA, 2015), 161–164.

17. Ramsamy, P., Haffegee, A., Jamieson, R., and Alexandrov, V. Using haptics to improve immersion in virtual environments. In *Computational Science–ICCS 2006*. Springer, 2006, 603–609.

18. Sakai, M., Fukui, Y., and Nakamura, N. Effective output patterns for torque display'gyrocube'. In *Online Proceeding of the 13th International Conference on Artificial Reality and Telexistence*, vol. 13 (2003), 160–165.

19. Tanaka, Y., Yuka, K., Fukui, Y., Yamashita, J., and Nakamura, N. Mobile torque display and haptic characteristics of human palm. In *Proc. ICAT* (2001), 115–120.

20. Tsetserukou, D., Sato, K., and Tachi, S. Exointerfaces: novel exosceleton haptic interfaces for virtual reality, augmented sport and rehabilitation. In *Proceedings of the 1st Augmented Human International Conference*, ACM (2010), 1.

21. Winfree, K. N., Gewirtz, J., Mather, T., Fiene, J., and Kuchenbecker, K. J. A high fidelity ungrounded torque feedback device: The itorqu 2.0. In *EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint*, IEEE (2009), 261–266.

22. Yano, H., Yoshie, M., and Iwata, H. Development of a non-grounded haptic interface using the gyro effect. In *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003. Proceedings. 11th Symposium on*, IEEE (2003), 32–39.