FeetBack: Augmenting Robotic Telepresence with Haptic Feedback on the Feet

Brennan Jones
University of Calgary
bdgjones@ucalgary.ca

Jens Maiero
Hochschule Bonn-Rhein-Sieg
jens.maiero@googlemail.com

Alireza Mogharrab
SIAT, Simon Fraser University
amogharr@sfu.ca

Ivan A. Aguilar
SIAT, Simon Fraser University
ivan_aguilar@sfu.ca

Ashu Adhikari
SIAT, Simon Fraser University
ashu_adhikari@sfu.ca

Bernhard E. Riecke
SIAT, Simon Fraser University
ber1@sfu.ca

Ernst Kruijff
Hochschule Bonn-Rhein-Sieg
ernst.kruijff@h-brs.de

Carman Neustaedter
SIAT, Simon Fraser University
carman@sfu.ca

Robert W. Lindeman
HIT Lab NZ, University of Canterbury
gogo@hitlabnz.org

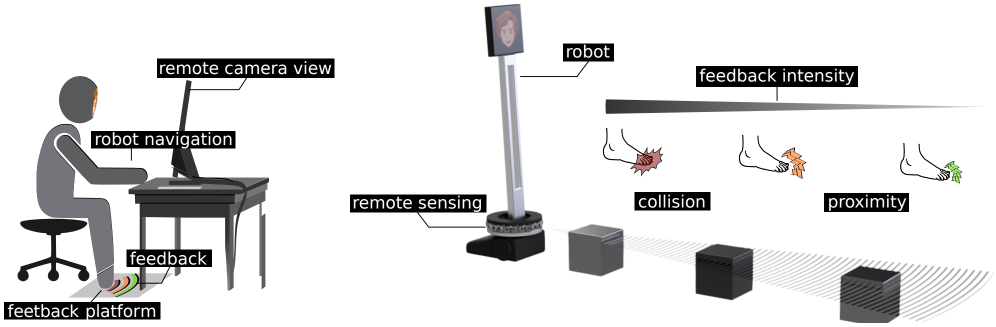

Figure 1: The FeetBack system. A user operates a Beam telepresence robot with a distance sensor ring attached to its base, which scans the remote environment. Based on the proximity of objects surrounding the robot, haptic feedback is provided to the user's feet, including vibrotactile cues for objects further away and a force event for collisions. Users place their feet on a purpose-designed foot haptics platform, and can either stand (Study 1) or sit (Study 2) while operating the robot.

ABSTRACT

Telepresence robots allow people to participate in remote spaces, yet they can be difficult to manoeuvre with people and obstacles around. We designed a haptic-feedback system called "FeetBack," which users place their feet in when driving a telepresence robot. When the robot approaches people or obstacles, haptic proximity and collision feedback are provided on the respective sides of the feet, helping inform users about events that are hard to notice through the robot's camera views. We conducted two studies: one to explore the usage of FeetBack in virtual environments, another focused on real environments. We found that FeetBack can increase spatial presence in simple virtual environments. Users valued the feedback to adjust their behaviour in both types of environments, though it was sometimes too frequent or unneeded for certain situations after a period of time. These results point to the value of foot-based haptic feedback for telepresence robot systems, while also the need to design context-sensitive haptic feedback.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

haptics; telepresence; navigation; robotics

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1 INTRODUCTION

Telepresence robots are mobile systems that allow people to remotely interact in a space through a drivable robot containing a video-conferencing system. They have made it possible for people

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to remotely participate in a variety of spaces, including remote attendance at academic conferences [29, 34], home schooling [30, 31], and remote office work and meetings [21, 35, 43]. Research has found strong benefits for being mobile in the remote space, such as increased feelings of social presence [21, 52, 53]. Despite the benefits, it is not always easy to remain aware of one's surroundings when using a telepresence robot, especially in crowded locations such as conferences and social gatherings where there are large numbers of people moving about, often unpredictably [34].

To address this challenge, we designed a haptic feedback system called *FeetBack*. When driving a telepresence robot, users place their feet inside the FeetBack system and receive haptic feedback on their feet when approaching obstacles in the remote space (Figure 1). The main goal is to provide users with additional non-visual feedback of what is around them in the remote environment so that they have better awareness and understanding of obstacles and make better navigation decisions. We are also interested in how feedback can be designed to enhance feelings of spatial presence, as greater presence can sometimes lead to more focus and investment in an activity or space [40]. We specifically chose the feet in order to keep the hands free for other tasks, including using a keyboard/mouse or gaming controller to drive the robot.

We conducted two studies with FeetBack. In Study 1, the goal was to gain an early understanding of how FeetBack affected users' behaviours in a virtual environment as well as their understanding and awareness of the space. We also aimed to understand the potential effects of the system on *spatial presence*: feelings of 'being in the space' [51]. The user drove a virtual telepresence robot in a virtual space (as opposed to a real robot in a physical space), allowing us to isolate the effects of the haptic feedback and to gain an initial understanding of effectiveness and ways to improve it. In Study 2, the goal was to understand how people would use and experience FeetBack (*user behaviour*) while driving a telepresence robot in a real environment with other people and obstacles. This involved driving and interacting during a remote university-campus tour as an exemplar activity. Study 1 was highly controlled, while Study 2 was exploratory to learn about real-world use of FeetBack.

We provide the following **contributions**: the FeetBack system caused users to alter their behaviour due to a heightened sense of responsibility (Study 1), making them more cautious (Studies 1 and 2). However, too much feedback caused a distraction to users (Studies 1 and 2), and some became desensitized to it (Study 2). In addition, FeetBack heightened spatial presence, realism, and sensations of self- and object-motion in a controlled virtual environment (Study 1), though we were unable to confirm this to be the case for more-complex real environments (e.g., scenarios such as campus tours; Study 2). These findings illustrate the value of haptic feedback for affecting user behaviours and helping them make better navigation decisions when operating telepresence robots. However, such feedback systems should be designed to be more context-sensitive.

2 RELATED WORK

Telepresence robots have been studied in a variety of settings, including academic conferences [29, 34], offices [21, 35], schools [30, 31], health care settings [18], and the outdoors [12]. Across these settings, researchers have found strong benefits, mostly stemming from the ability to be mobile in the remote environment with a form of 'physical body' [21, 29]. Mobility has supported people attending meetings and maintaining informal awareness in the workplace [21], attending social gatherings and mingling with others [29, 34], engaging in small group activities such as workshops [34], supporting long distance relationships [52, 54], establishing friendships [30, 31], and participating in learning activities [30, 31]. In these situations, because the user has a view into the remote space and can easily change that view by moving the telepresence robot, control over what is seen is in the hands of the remote user. This contrasts with other video conferencing setups (e.g., Skype) where the view is typically in the hands of the local user [15, 39].

Telepresence robots are not without their challenges. For instance, it can be hard to understand where one is spatially located when operating a telepresence robot [29]. This makes it challenging to manoeuvre them while performing other tasks like talking [29, 33, 42]. It can also simply be hard to know where one is in a building, especially if it is a new space for the user [29]. In crowded spaces, it is difficult to avoid obstacles or people with a telepresence robot [34]. Researchers have investigated many ways of increasing the amount of feedback that users get when interacting through a telepresence robot. This includes wider fields of view [14, 16] and audio feedback to know how one sounds in the remote space [16]. Yet there remains a design gap in providing telepresence robot users with means to help them receive feedback and improve their spatial awareness of obstacles while moving through a space.

The usage of **haptic feedback** by means of force feedback to enhance robotic telepresence systems has mostly been used to support manipulation tasks in teleoperation to improve accuracy and awareness (e.g., [9]). Using haptic feedback to support presence and awareness is far less common. Examples include improved situation awareness when haptic cues for collision avoidance are provided (e.g., [8, 17, 23]). However, all studies used hand-operated devices instead of providing feedback to the feet, which can provide an additional sensory channel that is largely unused in current telepresence robots despite being the body part that might naturally bump into things. Proxemics, the notion of proximity, has also found some interest in robotics, albeit foremost in relation to social aspects (e.g., initial work reported in [50]). Only a few studies have focused on the effects of haptics on navigation performance, including [22] that explored driving a mobile robot (non-telepresence). Results showed improved performance and presence However, systems were studied in environments that were neither complex (e.g., with many obstacles and people) nor dynamic (e.g., moving objects).

Using haptic feedback in relation to improving self-motion has been probed before, especially in virtual-reality systems. Embodied self-motion illusions (vection) have been studied for some time [13, 38] and can be elicited in stationary observers through various means, including visual cues [5], stepping along a circular treadmill [3, 37], or auditory cues like moving sound sources [20, 36] or foot steps [19]. Of notable interest are cues provided to the feet that relate to biomechanical movement [38], e.g., by simulating the roll-off process under the feet [19], showing improvements in self-motion perception. FeetBack is somewhat similar to the systems from [44, 45] that also used vibration patterns to elicit motion.

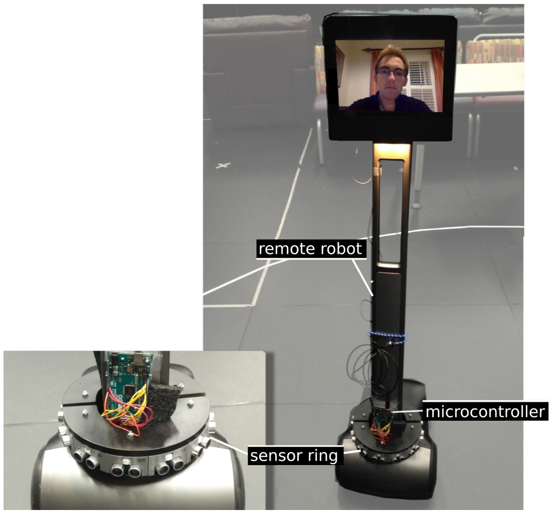

Figure 2: The ring consisting of 12 ultrasonic distance sensors attached to the Beam+ telepresence robot enables 360° coverage with a radius of up to 4m.

Vibration at the feet has received increasing interest in both research and applications, for an overview see [19, 28, 47, 48]. It has been used to provide navigation-related cues for self-motion and other areas: e.g., using vibrotaction to provide directional information has been explored through foot-based [47] and body-worn devices. For the latter, it has been shown that directional cues can be successfully provided by stimulating a certain side of the body (e.g., [25]). It has also been used to convey [4] or avoid collisions during navigation [1]. Collision avoidance relates to interfaces developed to indicate proximity, which has been studied for general 3D selection tasks to indicate how close the user is to a target [2, 26], but also has specific application in navigation systems. For example, SpiderSense [27] uses tactors distributed over the body to support navigation for the visually impaired. This kind of feedback is similar to a distance-to-obstacle feedback approach to communicate distances to surrounding objects [11] and wheelchair operation using a glove-based interface [46]. However, these systems do not have feedback granularity (providing directional proximity and collision feedback) like that afforded by FeetBack. Overall, related work has not fully explored how haptic feedback systems – especially feet-based systems – can be designed to enhance awareness and feelings of presence when operating a telepresence robot, and how users would experience such systems.

3 THE DESIGN OF FEETBACK

In many telepresence situations, the visual and audio channels are already being used for the primary activities that the user is engaged in within the remote environment (e.g., talking to people, looking at objects). The potential benefit of employing haptic feedback is that it uses an otherwise unused sense to provide spatial awareness while leaving other sensory channels free for other activities. We chose the feet as a natural place to provide this feedback in order to keep the user's hands free for other tasks. Compared to other body parts including hands, our feet are naturally associated with locomotion and locomotion direction, and are often the first part of the body that is touched when a person bumps into something. It may also be one of the best places on the body to provide directional (i.e., left, right, forward, backward, etc.) feedback, as it is easy to place sensors all around the users' feet [19] and keep them relatively stable (e.g., versus their hands, which may frequently move throughout use) when users operate the system while being seated. The feet typically point forwards or in the direction of walking, and thus they make a good virtual reference point. Finally, the feet are quite sensitive - together with finger, wrist, ear, and neck have been shown to have the highest perceivability and user preferences [6] and thus seem like a sensible choice when the feet are stationary as in our system. This paper also confirms there are other feedback locations suitable for vibrotactile feedback, which we further address in our discussion later. We assess these potential benefits in our studies to evaluate if the envisioned positive effects indeed occur.

We created FeetBack by extending a commercial telepresence robot called the Beam+, created by Suitable Technologies. The Beam is 134cm tall with a 25.4cm (10 inch) LCD monitor and a maximum speed of 2km/h (Figure 1, centre). Two wide-angle HDR cameras are attached to the robot. One camera points towards the floor to provide a navigational view (e.g., it shows other people's legs and feet), while the other points forward to show other people (e.g., their bodies and faces) and the environment. We extended the telepresence robot with a purpose-built sensor ring (Figure 2) consisting of 12 ultrasonic range sensors (HC-SR0). The FeetBack system is composed of a high-density wood and aluminium foot platform to which actuator blocks are attached (Figure 3). Users remove their shoes and place their feet within the foot platform. Though the system can be operated while wearing shoes, the feedback is more pronounced and better controllable when used without. Based on the distance sensors on the robot's sensor ring, users receive directional vibration cues when an object is sensed, and vibration frequency increases as the object gets closer to the robot. Once an object is in a predetermined collision range, a solenoid is triggered and provides a soft but noticeable impact to the user's foot. This mimics collision with a wall (brushing), but before actually hitting an obstacle, so users have enough time to avoid a collision.

3.1 Sensor Ring Design and Implementation

The distance range afforded by the sensors on the ring is between 2 and 400cm at a frequency of 40kHz, with a horizontal sensing cone of 30°. As such, the robot can detect objects in a radius of about 400cm around the robot. The sensors were connected to a Raspberry Pi 3 (Rev3 Model b+). In order to cover 360° and to avoid signal overlap, the 12 sensors are placed in three separate groups, each covering 120°, allowing control of all three groups sequentially with a delay of 50 ms, so that the entire area can be scanned within 150ms with an accuracy of up to 3mm. A microcontroller (Arduino Uno Rev3) manages the introduced grouping and collects distance data from the sensors, and passes it to a Python script on the Raspberry Pi. All distance data are then sent via WiFi to the remote-control PC using OpenSoundControl. Both the Arduino and Raspberry Pi are self-contained, powered by the robot's battery using the 5V connections provided. The 12 sensors required to cover 360°were mapped to the six vibrotactors on the FeetBack platform as follows: both the left and right sensor groups were explicitly assigned to the

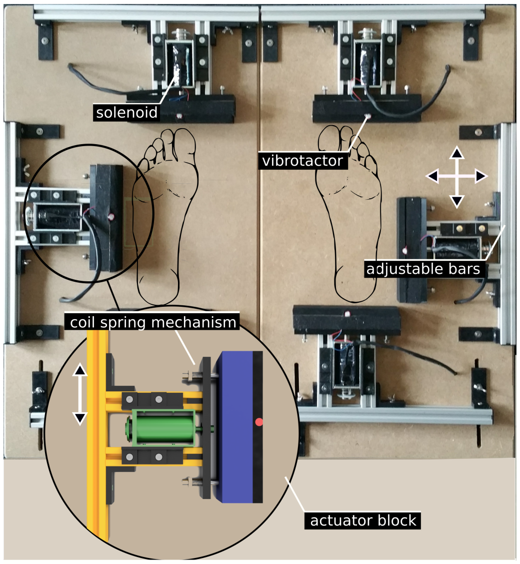

Figure 3: The foot platform consisting of six movable actuator blocks to support different foot sizes. In the close-up, the vibrotactor is marked with a red dot (proximity), the solenoid is shown in green and the movable axis of coil spring mechanism represented by an arrow (collision).

corresponding actuator blocks. Each front and back actuator block shared a front and rear facing sensor, plus a position-dependent neighbour that was added either to the right or left block. In order to guarantee unique feedback to the users, no cross-fade occurred; the feedback group that recognized the closest obstacle was activated.

3.2 Feedback Design and Implementation

The FeetBack platform contains a series of actuator blocks as illustrated in Figure 3, individually adjustable by moving the bars to support most foot sizes (between 21.0cm and 30.0cm). An actuator block consists of a vibration motor (Precision Microdrive 304-116), a Solenoid (ROB 10391, 36V), and a coil spring mechanism to provide a movable linkage required for collision feedback. In order to improve the user experience, a 1cm thick of compressible firm foam is attached to the foot-directed surface. A 5mm cylindrical vibration motor was integrated into the foam to provide vibrotactile proximity feedback. Three actuator blocks were attached for each foot and mounted at the front, the back, and the outer edge. All six locations of the actuator blocks reflect potential collision points of the real robot. The inner sides of the feet were not equipped with actuation blocks as there is no potential collision point at these locations. Two Arduino Mega were employed to control all actuator blocks, one for each foot. In addition, a graphical user interface displays the distance data of the sensors and allows the configuration of parameters, such as the proximity and collision range.

The FeetBack platform was designed to be easily adaptable to different foot sizes. It allowed us to easily and quickly adjust the vibrotactile contact points so that they touch the user's feet on all sides (front, back, left, right). While we could have instead designed a different form factor (e.g., a pair of shoes), we chose the platform design because it was a good balance between (a) making sure all of the motors touch at the right points (for directional feedback), ensuring proper feedback, and (b) being easy and quick to adjust to the various foot sizes of users . The form factor was not ideal (i.e., big and bulky); however, in our studies we mainly focused on the higher-level idea of providing gradual directional haptic feedback in telepresence situations instead of the underlying technology.

Our implementation supports two major modes for proximity feedback: *continuous vibration feedback* that increases the intensity and *pulsing feedback* that increases frequency in relation to the distance when an object is sensed. The closer an object gets to the robot, the higher the intensity or frequency of the vibration, respectively. Our implementation supports linear and polynomial proximity functions, and an adjustable range for activating proximity and collision feedback. Plus, the duration of the collision feedback and a maximal intensity for proximity are adjustable. Both the amplitude and vibration frequency are determined by the hardware and ranges from 0-1.4g (amplitude) and 0-300Hz (frequency), meaning a collision bump is clearly distinguishable from the vibration. Values chosen for our studies were based on pilot testing.

4 STUDY 1: VIRTUAL ENVIRONMENT

Following our design of FeetBack, we wanted to gain an understanding of how the system affected user behaviour and perceived spatial presence. To do so in a controlled way, we first studied FeetBack's usage in a virtual environment. We created a virtual simulation closely mimicking the visual cues and gamepad-based control of an actual telepresence robot, and had participants perform tasks in it.

4.1 Participants

We recruited 19 participants from the general public via social media, posters placed around our campus, and an online study-sign-up system for students in our department. Participants were aged 19-41 ($M = 24, SD = 5$), 12 women, six men, and one gender non-binary. Most were students, while the others were casual workers.

4.2 Methods

A simulation environment was used where participants standing in front of a large TV navigated a virtual robot through a virtual 3D scene. For the simulation of the distance sensors, a ray-casting approach was used to determine virtual distances, and mappings were created for intensity and proximity ranges. The study followed a within-subjects design. Participants had to navigate from a start to end position twice in two different, yet similarly-laid-out, virtual environments: once with FeetBack and another time without, in counterbalanced order. The display we used was an 147cm-wide TV screen (in 16:9 format) standing on a 75cm table. Participants stood about 1m from the screen, and stood in the same position in both conditions. The FeetBack platform was under their feet only during the FeetBack condition. In both conditions, they used a PlayStation-3 controller to navigate through the environment, using one control stick to move and turn around (up/down for forward/backward, left/right to turn left/right). Based on pilot testing, we used a collision range of 20cm and a proximity range of 2m with a linear proximity function. The maximum intensity of the tactile feedback was set to 100% (about ± 1G peak amplitude; about 240Hz) and the solenoids were driven with 24V.

Before each task, participants had a chance to practice driving in a virtual training environment with the interface condition they were about to use. The training environment was a small room containing objects, and participants were asked to practice driving until they got used to the controls, and in the case of the FeetBack condition, approach and collide with objects to explore what happens. Once participants said they were ready, they began the task. Participants were given an overhead map of the environment each time and told where the end position was. They were not told where their starting position was (i.e., they had to figure out where they were in the environment). To address spatial presence, the simulated environments contained walls, static obstacles, and moving people. In both conditions, a click sound played in the simulation when the subject collided with something. We added this to minimize confounds. As the actuators on the FeetBack platform make a noise when activated, we did not want there to be an absence of this noise in the non-FeetBack condition. We measured the subject's feelings of spatial presence, with a slightly modified version of the Witmer & Singer [51] questionnaire. The modified questionnaire asked 19 questions on 7-point Likert-scales and measured five aspects of presence, combining them to give an overall sense of presence:

- *Realism*: the extent to which the experience feels 'real'.
- *Possibility to Act*: the extent to which the participant feels like their actions will affect the environment.
- *Quality of Interface*: how user friendly the interface is.
- *Possibility to Examine*: the extent to which the participant feels like they can examine things in the environment.
- *Self-Evaluation of Performance*: the participant's own evaluation of their performance or abilities in the environment.

The modified questionnaire is the same as the original, except that we removed the three questions about sound and the two questions about haptics and touch (questions 20-24 in the Witmer & Singer questionnaire). We removed the questions on sound because there was not much sound in the virtual experience. We removed the questions on haptics and touch for two reasons: (1) haptics was not part of the experience for the no-FeetBack condition, and (2) we were instead interested in the effects that haptic feedback had on the other six individual factors measured in the questionnaire.

The orders of both feedback condition and environment layout were counterbalanced so about equal numbers of participants tried each condition and layout first, and so each condition was paired with each layout about an equal number of times. After completing the tasks, we conducted short semi-structured interviews to get participants' thoughts about FeetBack. Each task took about 5-10 minutes. The surveys took 10-15 minutes in total, and interviews lasted about 5 minutes. The quantitative data were analyzed using dependent (repeated-measures) t-tests. We used a Shapiro-Wilk test to test the normality of the data, and Wilcoxon Signed-ranks tests in place of t-tests when the data were not normally distributed. Thematic analysis was used to analyze the interviews.

4.3 Findings on Spatial Presence

Subject scores for overall spatial presence were significantly higher with FeetBack ($M = 5.30, SD = 0.83$) than without ($M = 4.93, SD = 0.94$; $t(17) = 2.42, p = .02$). For *realism*, we found that overall participants felt their experience was more realistic with FeetBack ($M = 4.98, SD = 1.12$) than without ($M = 4.21, SD = 1.49$; $t(17) = 3.13, p = .0061$). Our analysis did not reveal a statistically-significant effect for other aspects of presence measured by the questionnaire (*possibility to act*, *quality of interface*, *possibility to examine*, *self-evaluation of performance*; all $p > .05$). Looking at each of the individual questions in the questionnaire, we found a significant effect of interface on scores for three of the questions. For *"How compelling was your sense of objects moving through space?"*, participants ranked their scores higher with FeetBack ($M = 5.79, SD = 1.32$) than without ($M = 4.42, SD = 1.74$; $Z = 66.5, p = .0098$). Similarly, for *"How compelling was your sense of moving around inside the virtual environment?"*, participants also reported more compelling sensations of self-motion with FeetBack ($M = 5.26, SD = 1.63$) than without ($M = 4.52, SD = 1.81$; $Z = 42.5, p = .0449$). Lastly, for *"How involved were you in the virtual environment experience?"*, participants reported higher involvement with FeetBack ($M = 5.55, SD = 1.12$) than without ($M = 4.44, SD = 1.65$; $t(17) = 3.64, p = .002$). We did not find a significant effect for the other individual questions.

4.4 Users' Perceptions

Overall, participants generally enjoyed the FeetBack system and found it useful. Participants described the vibration as providing a tingling sensation at its strongest and being only a little noticeable at its weakest, and they described the collision feedback as a light tap which was sometimes surprising, but never painful. Participants said they consciously and subconsciously moved around the space more cautiously when using FeetBack than without, often being more hesitant in their actions. While this hesitance allowed participants to be more careful not to bump into things, it also prevented some participants from exploring more, likely due to being worried about bumping into something. Participants also found that haptic feedback increased their anxiety and stress.

P2: "Vibrations made me feel anxious at times (definitely more than having no vibrations). [...] It's good for alerting of the odd object, but when I'm moving through a narrow walkway, it feels more stressful than helpful."

Some participants found the feedback to be a bit distracting from the objectives of the task and thought that it made certain parts of the tasks more difficult. As a result, they thought that it should only be used in crucial circumstances (e.g., when awareness of a nearby object could prevent a collision). Participants generally found the feedback to be most useful when moving, or while being approached by a moving object while being stationary themselves.

P12: "It felt harder doing the task [with haptic feedback], but that's probably because my feet was getting constant feedback. My feet were vibrating almost all the time, so that was a little bit distracting."

Many participants said their investment and immersion in the activity increased with FeetBack, making them feel more responsible for their actions and associated consequences.

P17:"If I hit something while haptic feedback is on, I feel like it's my fault, because I felt it before hitting it. Without haptic feedback, I don't feel like it's my fault."

5 STUDY 2: TELEPRESENCE-ROBOT USAGE

Our findings from the first study revealed that FeetBack could improve overall spatial presence in a virtual space, though at times it was distracting and made people feel anxious. Based on these results, we wanted to explore FeetBack within real telepresence situations that are less controlled to see if the environment would make a difference. In our second study, participants used a telepresence robot to visit a university campus as a representative activity, experiencing many of the situations one would experience when using a telepresence robot at work or at a conference, e.g. talking to people, navigating. Our goals were to understand what **user behaviours** would emerge with FeetBack compared to without it.

5.1 Participants

We recruited 17 new participants through snowball sampling (word-of-mouth), social media (posts on Twitter and Facebook) and posters placed around our university. Fourteen participants had never used a telepresence robot before, and two participants had used a telepresence robot, but without haptic feedback. Participants included eight women and nine men, aged 19 to 55 ($M = 25, SD = 8$). Occupations covered a range of jobs and professions (e.g., university students, advisors, administrators). All participants owned smartphones and had used video conferencing technologies (e.g., Skype).

5.2 Methods

Our study was exploratory as we were mostly interested in learning about participants' reactions to the experience of FeetBack in the real world. We also wanted them to compare their experience to driving a telepresence robot without FeetBack. Based on results from Study 1, we adjusted the FeetBack parameters to a collision range of 20cm and a proximity range of 1m with a linear proximity function (Study 1 had 20cm collision range and a 2m proximity). The one-metre length was based on our measurements of all the spaces in which participants were to perform the tasks. The maximum intensity of the vibrators was set to 60% (about ± 0.6G peak amplitude; about 150Hz) and the solenoids were driven with 24V. Thus, the feedback was meant to be less intense compared to the first study. Participants were seated in front of a 55-cm-wide monitor with their feet placed on the FeetBack system (Figure 1) and used a PlayStation-3 controller to drive a Beam telepresence robot.

We designed eight tasks, where half were done with FeetBack and half without. Our goal was to provide opportunities for social interactions (e.g., asking people to open a door, press an elevator button, and ask a question from an advisor) as well as manoeuvring in both confined (e.g., narrow hallway, bookstore aisles) and wide-open spaces. When designing the tasks, we considered external factors such as the number of people in locations where each task took place, and physical obstacles along the way. We only chose tasks that would create a relatively consistent environment for each participant, though we recognize that each participant may have had variations in their task runs due to variations in the number of people present. We avoided tasks that would involve spaces with moving items of furniture, and we scheduled each run around the same time of day. Furthermore, we avoided instructing participants on how to perform each task specifically (e.g., we let participants decide just how close they came to people or obstacles). This was so participants could explore different ways of manoeuvring and determine what was most comfortable for them. Participants received a map showing the locations of each task.

Task 1 - Poster Board: Participants had to navigate through a narrow hallway, find a specific bulletin board, and take a screenshot of a poster of interest to the participant. The goal was to drive in narrow spaces, requiring participants to carefully approach a wall with posters, and move along the wall.

Task 2 - Student Advisor: Within the same hallway, participants had to find a student advisor, go into their office, and ask them to describe a specific course. The goal was to move in a confined office and directly interact with another person.

Task 3 - Bookstore: Participants had to drive through a 'handicap door' and go to a nearby campus bookstore. Once there, they had to find out the price of a specific book. The goal was to interact with passersby in order to have the handicap-door button pushed for them. We then wanted them to explore narrow walkways between shelves, and search for a specific item.

Task 4 - Find a Person: Participants had to travel across an open mezzanine to a large collection of tables and chairs outside of a coffee shop, find a specific person, and park next to them. The goal was to search for something at a distance and also navigate around many chairs, table legs, and people.

After completing these four tasks, participants completed two questionnaires. The first was the same presence questionnaire that was used in our first study (based on [51]), but we re-added the questions about sound (questions 20-22 in the original questionnaire), as Study 2 included real-world sound. We still excluded the questions related to haptics and touch (questions 23 and 24 in the original questionnaire). The second questionnaire was the NASA Task Load Index (TLX) [10] to measure perceived workload on six scales. In addition to its effects on spatial awareness, we were also interested in finding out if FeetBack affected participants' sense of how hard they were working or concentrating mentally. Participants were asked to rate *mental demand, physical demand, temporal demand, performance, effort*, and *frustration* from 'Very Low' to 'Very High' using 7-point Likert-scales. Next, participants switched conditions and repeated the first four tasks, but in reverse order. We modified the tasks such that each involved looking for new information. For example, participants had to find a different person in the crowded table configuration, look for a different textbook in the bookstore, etc. Once done with all tasks, participants drove back to the start point of the study. They then completed the spatial presence and NASA TLX questionnaires for the second condition. The order of conditions (with or without FeetBack) was counterbalanced across participants. At the beginning of the study session and between Tasks 4 and 5 (when they are switching conditions), participants were asked to practice driving the robot and explore the feedback mechanisms available (in the case of the FeetBack condition, they were asked to drive close to objects to explore the feedback they would receive). Participants were asked to do this until they said they were used to the interface condition. We conducted semi-structured interviews with each participant after completing the tasks. The first phase of the interview focused on understanding their previous experiences using telepresence technologies and video conferencing systems. For example, we asked, *"Tell me about your experiences using telepresence technologies before the study."* The second phase of the interview focused specifically on their experiences using the robot with FeetBack in the study. We asked questions such as, *"Was there anything that stood out about* *your experience navigating the robot?"* and *"How would you describe the sensations you felt on your feet?"*

Participants operated the telepresence robot from a room in our lab, while the actual robot was located in a different place on the university campus. Interviews and questionnaires were conducted in-person, immediately after performing the tasks.

5.3 Data Collection and Analysis

The tasks took about 40 minutes in total (~20 minutes for each condition), while the surveys took 10-15 minutes. We audio-recorded and took detailed notes of all our interviews with consent of the participants. Interviews lasted about 15 minutes, and all interview data were transcribed. We recorded video of the user driving the robot via a screen capture showing the robot's two cameras.

We performed thematic analysis on our interview data to categorize it and identify main themes. Two researchers analyzed and coded the qualitative data, and reviewed the video to provide additional understanding of what was happening. The main themes were *spatial presence*, *trust in the haptic feedback*, *behaviours to avoid collisions*, and *contextual differences that affected the feedback*.

The quantitative data were analyzed in the same way as in Study 1. P10 was unable to complete half of the tasks because of battery issues on the robot. Thus, P10's data is not included in the quantitative analysis (though it is included in the qualitative analysis).

6 FINDINGS

6.1 Navigation and Obstacle Avoidance

In our interviews, 11 out of 17 participants said that they found FeetBack useful to understand the remote environment better. They said they could feel if they were getting too close to obstacles and if someone was moving behind or next to the robot, especially when they could not see them on the screen. Three participants said FeetBack was an effective background warning system that provided additional information on top of what they could see. Two participants found it most useful when driving in an unfamiliar environment for the first time. However, they did not have a strong preference for using it once they had learned more about the remote space and got used to driving there. In addition, participants believed FeetBack helped them to bump into fewer objects and people in the remote environment. For example, video analysis showed that three participants often kept more distance between the robot and the objects compared to when they were not using FeetBack.

P13: "I think having vibrations helped me. When I was taking the turn I didn't realize I was gonna hit a chair, ...so having a vibration on my right foot made my eyes go near the right side [of the screen] and then I got to know that there's a chair and I have to move."

The haptic feedback also affected the paths participants took when driving the robot. For instance, in Tasks 1 and 2 where they had to drive through a narrow hallway and a ramp, some participants drove in the middle of the ramp so they would receive the least vibration, while some drove on the side so they would leave more room for others walking.

Additionally, because of the haptic feedback, three participants said they did not look at the bottom camera feed as much as they did when not using FeetBack. One participant said he felt more comfortable when driving with FeetBack and relied on the system to tell him if there were obstacles nearby. Therefore, he paid less attention to the obstacles visible on the bottom-camera. Four participants said they did not trust the feedback as much, as it eventually triggered too often and became too distracting. They said they mainly relied on the camera feeds to stay alert to nearby obstacles.

We observed that some participants chose to keep more distance between the robot and the people they were interacting with. One participant, while performing Tasks 3 and 5 in the bookstore, kept less distance to the rear bookshelf and more distance from the cashier, receiving more vibration at the back of the foot. Although this behaviour was seen in a few cases, it was not consistent among all participants. That is, some participants, on occasion, performed the opposite—keeping less distance to the person and more distance to the object. This behaviour suggests that there might be other social and environmental factors that affect behaviour.

6.2 Reactions to Feedback and Collisions

The feedback had clear effects on the behaviour of participants. For some, it meant changing their behaviour immediately and, for others, it meant questioning the feedback and thinking through what they should do next. Nine out of 17 participants took immediate action in order to avoid hitting objects and people whenever they received collision feedback; they would immediately slow down or stop the robot when the feedback occurred. This immediate reaction to collision feedback mostly happened in confined spaces where there were many obstacles within the collision range.

P10: "The kick really helped out in providing feedback that you're getting way too close that you'll hit it."

Other participants were not sure whether the feedback meant that they had collided with an obstacle or merely that they were getting too close to one. Thus, they could not clearly differentiate what in particular the feedback was alerting them to. In these cases, subjects would either continue on or investigate. For example, some subjects used the bottom-facing camera to learn and understand when the collision feedback was being triggered, and this was seen as being useful. In some cases, an immediate change in direction of the robot as a response to the feedback led to colliding with other nearby objects. For instance, P1 found the frequency of collision feedback to be overwhelming since he lost focus and collided with some chairs in Task 4. Similarly P6 collided with a Christmas tree placed by the wall near where she had to take a screenshot of a poster (Task 1). These participants often described the collision feedback as shocking or surprising and said they got distracted by it, which led to them losing concentration on their driving.

P5: "If the task is critical or you are in some sort of situation that you need like act fast, when something is kicking you, you solely get shocked and you jump off; it's not something good."

6.3 Usefulness Based on Context

Participants felt that the usefulness of FeetBack varied with the context of the task they were performing. Context refers to the amount of space that was available around the robot (e.g., confined vs. wide-open, the number of obstacles or people around). Before the study, we had measured the minimum width of all the spaces in which participants were to perform the tasks and used this to set the proximity range to 1m. This meant that feedback would occur when the robot was within 1m of an object. This decision was made to ensure that participants received relatively consistent feedback throughout the tasks they performed. However, we found this configuration was not as useful for some of the task contexts. For instance, the configuration was seen by participants to be useful for manoeuvring in the bookstore and the advisor's office because the spaces were more constrained, and participants wanted to avoid bumping into things. However, this setup and the associated feedback was less useful when driving in spaces with consistent width and straight paths, such as hallways and ramps where the walls were within 1m. In these cases, participants received constant haptic feedback while there was nothing they needed to avoid.

P5: "On the ramp, the robot was not in danger but it kept vibrating; it makes me ignore the feedback" P13: "Yeah, I think only one thing that I would change was it vibrates when you're really far, like when you're not actually touching an object. I was not sure why that was happening. So once, it started vibrating, but when I looked there was nothing around. So I was not sure why that vibration happened."

Additionally, confined spaces with multiple obstacles in the collision range triggered collision feedback several times and on different sides of the user's feet. This caused some participants to feel overwhelmed, and, in turn, made the feedback less useful for them.

P1: "Driving the robot between the chairs in the mezzanine, the [collision feedback] was startling, because all of these kicks were happening at the same time. I was so close to all those chairs. It was hitting me from all sides."

6.4 Spatial Presence and Workload

Participant scores for overall spatial presence were similar with ($M = 5.09, SD = 0.49$) and without FeetBack ($M = 5.06, SD = 0.69$) and did not differ significantly ($t(15) = 0.258, p = .8$). The spatial presence subscores were similar with and without FeetBack, with no significant effects: *realism* ($t(15) = 0.086, p = .93$), *possibility to act* ($Z = 12, p = .79$), *quality of interface* ($t(15) = 0.063, p = .95$), *possibility to examine* ($t(15) = 1.05, p = .3$), *self-evaluation of performance* ($Z = 20, p = .44$), and *sound* ($Z = 22.5, p = .16$). Similarly, the individual questions from the presence questionnaire revealed no significant effects for any of them (all $p > .05$). Thus, unlike in the first study where FeetBack enhanced feelings of presence and involvement in the environment, we did not find that these effects transferred to the telepresence situations tested. Regarding the perceived workload (NASA TLX), scores were similar with ($M = 36.90, SD = 18.09$) and without FeetBack ($M = 36.60, SD = 16.15; p > .05$). Scores for each of the raw and adjusted values for each of the six scales on the TLX questionnaire also did not differ significantly between conditions (all $p > .05$). Thus, we did not find any noticeable difference in either presence or perceived workload when driving the robot with FeetBack vs. without.

7 DISCUSSION AND CONCLUSIONS

Overall, our studies showed that FeetBack was understandable to users and had a positive effect on user behaviour in terms of improved awareness and subsequently more cautious driving. However, there were times when the feedback was not needed and participants could understand the environment from the camera views. At other moments, the feedback was too intense and continuous. This suggests value in context-dependent systems that can have a better understanding of the navigation behaviour of the user, types of obstacles around them, and the kinds of behaviours they want to instill for such situations. Naturally, providing context-dependent feedback solely on the spatial configuration of the scene is challenging. For example, in crowded locations movements can be highly unpredictable [34]. Designers could explore feedback mechanisms that consider context by addressing the range and density of objects surrounding the user, as well as the movement speed and time-to-contact with objects. For example, objects could be clustered based on range. Simultaneously, one could measure the movement speed of the robot and adjust feedback accordingly. Designers could also explore feedback that is dependent on time-to-contact. This would allow users to always have sufficient time to stop the robot before they hit an obstacle (similar to 3D manipulation support systems, e.g., [2, 26], no matter how fast or slow they drive. This would reduce unnecessary feedback when slowly manoeuvring around or approaching obstacles, but without any danger of running into them, similar to [1]. Conversely, if the user drives faster, the distance where proximity feedback is first provided would increase to provide sufficient reaction time to adjust.

The haptic feedback in our system warned about the existence of a potential danger, yet it did not do much to help the user understand what that danger was, how much of a risk it posed, or what they could do to avoid it. This could be one of the reasons why participants became desensitized to the feedback, as they started to ignore it after it became too frequent and they realized that it was not providing additional useful information beyond the *existence* of a potential danger. Providing this additional information may be essential for the feedback to ultimately become useful to the user. Coupling haptic feedback with other forms of feedback (e.g., audio, visual) could be one way to accomplish this.

While we explored how directional haptic feedback influences a user's perceptions of the remote space, we did not focus much on methods for controlling the robot; though this would be sensible to explore for future work. For example, it may be worthwhile to explore putting both feedback and control on the feet. There are various possible ways of doing this: e.g., leaning-based control [19, 32] or foot/walking-based control [7, 41, 49]. Also, the design of the feedback device can certainly be optimized for a smaller footprint and a less "technical" appearance. Other form factors also come to mind, such as shoes or a belt-worn device (similar to [24]). While our main premise for providing feedback to the feet was the association with walking (hence, movement) and using a body part that is not being used for other tasks, it would be interesting to compare our device to other feedback locations and types. Future work should also explore the behaviors and preferences of experienced drivers. Our results are limited in that participants were all novice telepresence robot users. More advanced users might find systems like FeetBack as not useful since they could have already developed strategies for driving in complex environments. Furthermore, there could have been a novelty effect, and thus confirmation bias, from our novice participants. Finally, FeetBack may also be a useful extension for navigation systems in general [28], and particularly for visually-impaired people., e.g., supporting accessibility in games or real-world wheelchair operation.

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