Multimodal Haptic Interface for Walker-Assisted Navigation

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***Abstract*— This study investigates the efficacy of a haptic interface, aiming to offer the walking frame users accurate, intuitive, and easily understandable directional cues. The research introduces a novel haptic feedback interface incorporated into a walking frame to enhance navigation assistance. The haptic handle encompasses three distinct haptic feedback modalities: vibration, skin stretch, and combined feedback. Ten participants, all in good health, engaged with the haptic handle for navigation. Across all three haptic feedback methods, 60% of participants found the combined feedback to be the most effective, while 40% favoured the vibration feedback; none selected the skin-stretch feedback. Comparative analysis revealed significant disparities between vibration and combined input regarding velocity (p-value: 0.04). These findings emphasize the haptic handle's capacity to give users an instinctive perception of directional cues, thus offering a promising avenue for assistive navigation.**

I. INTRODUCTION

The proportion of older people has exhibited a growing trend in almost every country this century [1]. The World Health Organisation's (WHO) latest report shows that the global population aged 60 and over will more than double from 1 billion in 2020 to 2.1 billion in 2050 [2]. As people age, they may lose physical function, sensory impairment and long-term medical conditions [2].

Conventional mobility aids such as canes, crutches, and walkers are widely used to help older people, by preventing falls, assisting with walking, avoiding obstacles and guiding them [3], [4]. These devices can increase self-confidence and independence in their daily lives. However, canes and crutches only allow the user partial physical support and some somatosensory feedback from ground reaction forces. Wheeled walking aids can provide weight support to the user and, when equipped with sensors and actuators (smart/robotic walkers (SW)), can provide safer and more reliable navigation, obstacle avoidance, and walking assistance [5].

Older adults may face visual and auditory impairments, and for those without these impairments, visual and auditory feedback can overwhelm the user. Therefore, haptic feedback might be a suitable alternative [6]. The common haptic feedback includes vibration, electro-tactile, and mechano-tactile [7]. In this study, we used vibration and mechano-tactile, i.e., skin-stretch. Electro-tactile feedback is not used as it might cause discomfort to the user [8].

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In this article, we describe the design of new haptic handlebars that assist users in navigating their way to destinations by providing vibration and skin-stretch feedback. Our research aims to determine whether this haptic interface can offer users accurate, intuitive, and easily understandable directional cues. This is the first study to compare two different haptic feedback methods, within an navigational system.

II. RELATED WORKS

SWs use different approaches to provide users with navigation and obstacle information. VA-PWMAID [9] and GUIDO [10] use audio feedback to provide navigation information to users, and the user has complete control of the walker. Both NOMAD [11] and I-WALKER [12] developed a haptic interface using force sensors mounted on the handlebars. These SWs guide users according to a path-planning system. However, in a dangerous situation, the SW stops or forcibly changes the direction and speed of the SW's movement. The AGoRA SW [13] does not use feedback methods to guide the user. Instead, it detects the user's intention to move based on the interactive forces between the user and the walker's handlebar and controls the velocity of the walker's movement.

Vibrotactile systems transmit information through different frequencies and intensities [14]. Skin-stretch feedback conveys information to the user by directional stretching of a specific skin area [15]. *Sánchez et al.* demonstrated that users could feel vibration signals while walking and standing [16]. *Wachaja et al.* presented a walker and a vibrating handle. It also used a vibrating belt to provide the user with navigational information [17], [18]. Instead of mounting the vibration motor on the walker, *Scheggi et al.* proposed a vibrotactile bracelet to improve navigation in complex environments [6]. In *Scheggi et al.*'s work, the FriWalk [19] walker uses a vibrating bracelet to guide the user. However, FriWalk mounts a sensing interface and actuation technology on a commercial walking frame. *Pan et al.* proposed a sensory-enhanced mobility aid based on a walker that provides real-time orientation information to the user through skin-stretch feedback to improve their posture and assist with balance [20].

The majority of studies have concluded that the use of vibration feedback in isolation is not only limiting but also leads to discomfort for the user. That is because the constant perception of vibration reduces a person's sensitivity [18]. Using skin-stretch feedback alone may cause users to be insensitive to skin-stretch because of the constant perceived

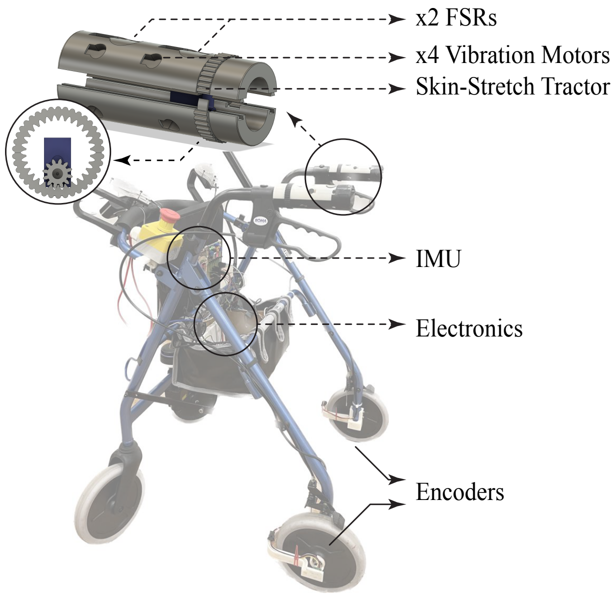

Fig. 1. Illustration of the Smart Walker with the haptic handlebars. Each handle contains a force-sensing resistor (FSR), vibration motors, and a servo motor for skin-stretch.

skin-stretch [20]. Moreover, the skin-stretch feedback configured on the SWs mentioned above was not used as part of the navigation system but only examined whether the user could perceive it while standing and walking.

III. METHODOLOGY

A. Interaction Platform

The interaction platform involves the development of new haptic handlebars placed on a commercial rollator frame. It was modified with sensors and hardware for navigation and experimental data analysis (See Fig. 1).

1) BRL Smart Walker: The SW is a passive mobility aid developed at Bristol Robotics Laboratory (BRL). On the rear wheels, encoders (AS5600 Magnetic, Osram, Germany) estimate the walker frame's movement. An Inertial Measurement Unit (IMU) (BNO080, SparkFun, USA) is placed at the bottom of the padded seat to estimate the SW's orientation. The combined use of these two sensors provides SW with odometry. The onboard Raspberry Pi 4 Model 4GB (Raspberry Pi Foundation, UK) runs Debian with the Robotic Operation System (ROS) framework.

2) Haptic Handlebars: New handlebars were designed with sensors and actuators that do not interfere with the user's tactile sense. Also, the handle should be easily removable to install and replace new sensors or actuators. The design builds on the previous work [16] to increase the number of vibration motors, adjust the skin-stretch ring's design, and add two FSRs (402, Interlink Electronics, USA) to detect if the user is holding the handlebar correctly (See Fig. 1).

The vibration cues are generated by mini vibration motors (316040001, Seeed Studio, China) mounted in the upper and lower parts of the handle, with two motors

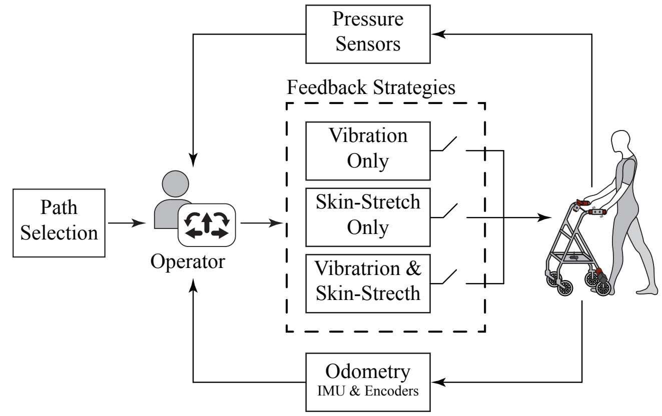

Fig. 2. Illustration of the human-robot interaction loop.

TABLE I
FEEDBACK STRATEGIES FOR THREE HAPTIC FEEDBACK METHODS.

Cues	Vibration	Skin-stretch	Combined
Turn left/right	Left/right motor vibrates for 0.3s.	Left/right servo rotates left/right for 0.4s.	Left/right servo rotates left/right for 0.4s.
Turn around from left/right side	Left/right motor vibrates twice.	Left/right servo reciprocates for 1.5s.	Left/right servo reciprocates for 1.5s.
Go straight	All motors vibrate twice.	Both servos reciprocates for 1s.	All motors vibrate twice.
Goal reached	All motors vibrate for 1s.	Servos rotate one direction for 2s.	All motors vibrate for 1s.

in each section. The skin-stretch cues are generated via a modified SG90 servo motor. The modified SG90 servo motor (TIANKONGRC, China) can rotate 360° by fixing the potentiometer and removing the stop mechanism from the master gear. A spur gear mounted on the SG90 triggers a tangential movement of the tractor against the user's hand.

3) System Operation: Fig. 2 shows the control loop of the haptic interface. The FSR data are transmitted to the system when the participant holds the handlebars. A calibration test determines the exerted pressure's threshold value. If the participant holds the handlebar correctly (palm in contact with the FSR, index finger on the bottom of the skin-stretch ring), and the pressure exerted by the participant exceeds the threshold, navigation information is published to generate directional cues through the haptic feedback handlebars. The odometry data transmitted to the computer calculates the participants' walking distance and velocity. All device communication is based on the ROS framework [21].

Three different haptic feedback strategies were developed for the navigation: vibration, skin-stretch and combined (Table I). The combined feedback consists of half of the directional cues from each of the vibration and skin-stretch feedbacks. These strategies were chosen based on the previous work in [6], [16], [20].

B. Experimental Protocol

1) Subjects: Ten healthy people participated in the study (70% males, 30% females, 31.0 ± 13.7 years old). The inclusion criteria were subjects over 20 years old with no visual impairment. The University Research Ethics Committee

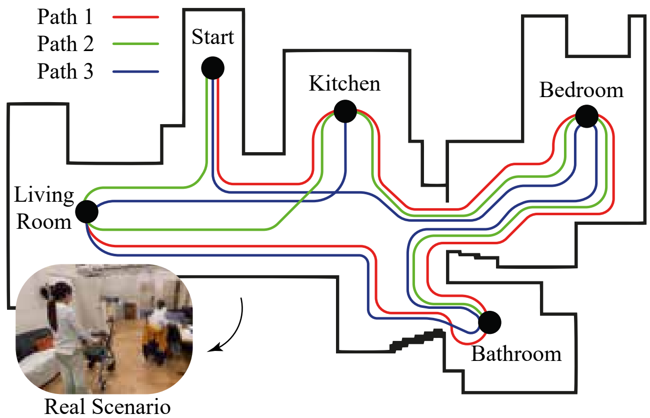

Fig. 3. The map of simulated living studio and predefined paths for the experiment. The red, green and blue paths correspond to those followed using vibration feedback, skin-stretch feedback and combined feedback, respectively.

approved the protocol of this experiment. All the participants were informed about the purpose of the experiment and the use and storage of relevant experimental data. They signed the informed consent before the start of the experiment. Participants were free to leave the experiment or refuse the use of their data at any time.

2) Experimental Procedure: After providing a signed consent form, a monofilament test was performed with a monofilament pen [22]. This test was designed to verify the subject's hand perceptual abilities.

All subjects received the same training via a pre-recorded video and experienced all the directional cues. The study consisted of three different experiments, one per feedback strategy. The experiment was carried out in the Assisted Living Studio at Bristol Robotics Laboratory, lasting between 10 to 15 minutes. Participants were required to reach a destination using the three feedback strategies in each experiment. Each feedback strategy is assigned a goal in the reference path. Although the strategies used by the participants to reach the goal were the same, the sequence of commands during arrival was different. This is to avoid the learning effect. Fig. 3 shows the reference path, the selected goals, and an illustration of the real scenario.

A pre-trained operator sent the directional cues to the haptic handlebar and the ROS visualization system was used to track the walker's motion and the selected goals. Thus, the paths did not have specific distances travelled, number of turns, or directional cues. These data are dependent on the participants' walking conditions during the experiment. In this sense, the user study aimed to verify whether the haptic interface could provide intuitive navigation information to the user rather than comparing path-following performance.

3) Quantitative Assessment: To analyse the user's performance, duration and distance were recorded. As each participant travelled a different distance, these two variables were only used to calculate speed. In addition to that, every directional cue published by the system is recorded so that accuracy can be calculated by comparing the number of times the system published directions, and the number of times the participant walked in a direction different from that published by the system.

TABLE II

ACCEPTANCE AND USABILITY QUESTIONNAIRES USED IN THE EXPERIMENT.

No.	Questions
1	The **vibration** feedback provides intuitive directional cues
2	The **vibration** feedback strategy is easy to understand.
3	In this session, perceived **vibration** signals did not cause any discomfort.
4	The **skin-stretch** feedback provides intuitive directional cues.
5	The **skin-stretch** feedback strategy is easy to understand.
6	In this session, perceived **skin-stretch** signals did not cause any discomfort.
7	The **combined** feedback provides intuitive directional cues.
8	The **combined** feedback strategy is easy to understand.
9	In this session, perceived **combined** signals did not cause any discomfort.
10	The training is sufficient to understand and remember the feedback strategies.
11	I think the haptic handlebar guides me well.
12	After completing the three experiments, which haptic feedback method do you prefer? Why?
13	Do you have any suggestions after your experience with the haptic handlebar?

4) Qualitative Assessment: The qualitative assessment is based on previous studies with SW using haptic feedback [13], [17], [20], [23], [24]. In this experiment, a questionnaire is designed to investigate the intuitiveness, comfort and ease of use of the haptic signals provided by the handles (See Table II). Except for questions 12 and 13, all questions used a 5-point Likert scale from 0-4 (0 = strongly disagree, 4 = strongly agree). Questions 10 and 11 asked participants about the effectiveness of the training before the experiment and the usability of the haptic handlebar.

5) Statistical Analysis: The MATLAB software (R2022b, MathWorks, USA) was used for the statistical analysis of all data acquired in the quantitative and qualitative assessments. A Shapiro-Wilk normality test was performed on all recorded variables. In addition, a Friedman test was performed to determine if there were any statistically significant differences between the data when the data did not satisfy a normal distribution. Furthermore, post hoc tests were conducted using the Wilcoxon test when the Friedman test showed significant results. When the data followed a normal distribution, One-way ANOVA was used to determine the differences between the same types of parameters collected by users when experimenting with different haptic feedback methods. When the data showed a difference, multiple comparisons were made between groups using Tukey's test. Finally, the paired Mann-Whitney U test was used to analyse the scores on the Likert scale of the questionnaire. The significance level for all tests was p<0.05.

IV. RESULTS

The results of the monofilament test revealed that all participants exhibited unimpaired hand perception. That was an expected result because most of the subjects were young. As outlined in the monofilament test procedure documented in [22], the participant's hand perception is normal if they can feel the lightest filament.

A. *Quantitative Results*

Table III summarises variables recorded during the study and the result of the Shapiro-Wilk test. Fig. 4 compares the differences between speeds in experiments. Fig. 5 compares the differences between parameters that yielded valid p-values after the Shapiro-Wilk test. The reason for the zero accuracy for turning around from the left in Fig. 5 is that this directional cue was only published once in one of the participants' experiments and was not perceived correctly by that participant.

The results showed that participants walked the fastest using combined feedback (CF) during the experiment. Among the three haptic feedback strategies, both vibration feedback (VF) and CF were not 100% accurate in half of the total six directional cues, except skin stretch feedback (SSF), which had only one directional cue that was not 100% accurate. In all three haptic feedback strategies, the accuracy of the "go straight" cue did not reach 100%. The accuracy of CF was the highest among them. In addition to the "go straight" cue, the "turn around from left/right" cue was also less than 100% accurate in VF. In CF, the cues less than 100% were "turn left" and "turn around from left".

The result of velocity after the Shapiro-Wilk test followed the normal distribution. The One-way ANOVA test was used to compare the difference in velocity in different feedback methods. The velocity only showed a significant difference between VF and CF ($p - value = 0.04$). Friedman test was used to compare the accuracy of six directional cues to verify whether there were significant differences between the haptic feedback methods. The test results showed that the accuracy of the four directional cues with valid p-values demonstrated in Table III did not differ significantly between the three haptic feedback methods.

As can be seen, SSF is better than the other two methods. Although the walking speed using this method is not the fastest, it has the largest number of directional cues that reach 100% perceptual accuracy.

B. *Qualitative Results*

Fig. 6 shows the participants' responses to the questionnaire using a Likert scale. Table IV shows the mean and standard deviation of the three items of the questionnaire. The results showed that participants were more satisfied with the VF's intuitiveness and ease of use. The SSF scored the same as the CF for intuitiveness and ease of use. Regarding comfort, VF and CF scored the same. However, some participants did not consider the use of SSF comfortable.

TABLE III
SUMMARY OF PARAMETERS AND SHAPIRO-WILK TEST. VF: VIBRATION, SSF: SKIN-STRETCH, AND CF: COMBINED FEEDBACK.

Parameters	VF	p-value	SSF	p-value	CF	p-value
Velocity [m/s]	0.25 ± 0.05	0.57	0.27 ± 0.07	0.34	**0.32 ± 0.08**	0.14
Turn Left Accuracy [%]	**100.00 ± 0.00**	NaN	**100.00 ± 0.00**	NaN	98.75 ± 4.52	p<0.01
Turn Right Accuracy [%]	**100.00 ± 0.00**	NaN	**100.00 ± 0.00**	NaN	**100.00 ± 0.00**	NaN
Turn Around From Left Accuracy [%]	90.00 ± 31.62	p<0.01	**100.00 ± 0.00**	NaN	90.00 ± 31.62	p<0.01
Turn Around From Right Accuracy [%]	96.67 ± 10.54	p<0.01	**100.00 ± 0.00**	NaN	**100.00 ± 0.00**	NaN
Go Straight Accuracy [%]	92.97 ± 11.02	p<0.01	98.75 ± 3.95	p<0.01	**99.17 ± 2.63**	p<0.01
Goal Reached Accuracy [%]	**100.00 ± 0.00**	NaN	**100.00 ± 0.00**	NaN	**100.00 ± 0.00**	NaN

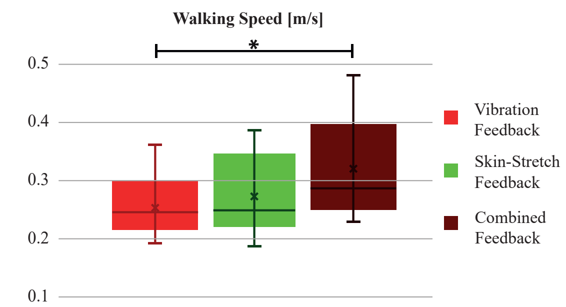

Fig. 4. Comparison of walking speed between feedback modes.

Fig. 5. Comparison of accuracy of directional cues with valid p-values in three experiments.

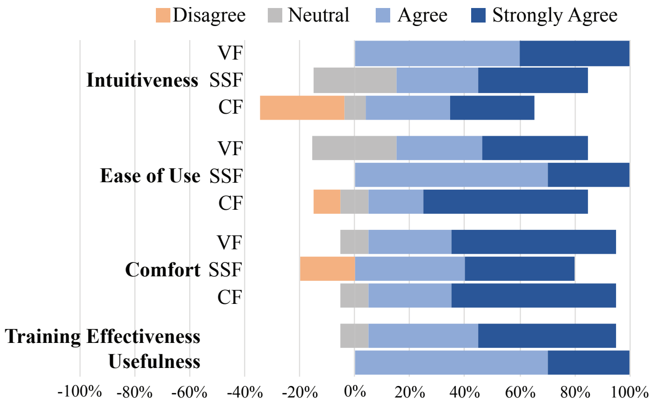

Fig. 6. Participants' feedback on the intuitiveness, ease of use and comfort of the three haptic feedback methods, as well as on the training effectiveness and usefulness. VF: Vibration Feedback, SSF: Skin-Stretch Feedback, CF: Combined Feedback.

TABLE IV
QUESTIONNAIRE RESPONSE FOR THREE ASPECTS. VF: VIBRATION FEEDBACK, SSF: SKIN-STRETCH FEEDBACK, CF: COMBINED FEEDBACK. (MEAN ± STANDARD DEVIATION)

Items	VF	SSF	CF
Intuitiveness	**3.40 ± 0.52**	3.10 ± 0.88	3.10 ± 0.99
Ease of use	**3.50 ± 0.71**	3.30 ± 0.48	3.30 ± 1.06
Comfort	**3.50 ± 0.71**	3.00 ± 1.15	**3.50 ± 0.71**

The results of the paired Mann-Whitney U-test with two-tailed hypothesis conditions showed no significant differences between the three haptic feedback methods for intuitiveness, ease of use and comfort. Additionally, participants answered two open-ended questions. These two questions reflected the participants' preferred haptic feedback methods and some suggestions. There were 60% of people who preferred CF, and 40% preferred VF. Participants who preferred CF felt that this method provided a clearer and more intuitive signal. Participants preferred VF because they felt that CF had too many combinations of feedback signals that were difficult to remember and could cause confusion. Almost all participants think the SSF have drawbacks, such as not being able to exert too much force on the skin-stretch ring and the skin-stretch ring not fitting well into the handle, resulting in unclear feedback signals.

V. DISCUSSION

The outcome of the monofilament test was anticipated, as most of the participants are healthy young volunteers and all have normal sensory perception. This helps to establish a baseline for feedback perceptions.

The results in Table III, the number of participants completing the experiment using SSF with directional cue perception accuracy reached 100% higher than the other two methods. However, participants walked the fastest when completing the experiment using CF. This is a new result as no literature exists comparing two haptic feedback and their combined version. There were no significant differences in any of the parameters between VF, SSF, and CF except for the comparison of VF and CF which were significantly different in velocity. The reason for the increased velocity may be that CF is always the last strategy to be used for experiments. The perceived accuracy of the number of directional cues was lower in the VF and CF than in the SSF, maybe because the resonance between the haptic handle and the walker prevented participants from clearly perceiving directional cues, and the CF required too many feedback strategies to memorise.

The results from the quantitative assessment can be utilized to improve the experiment design. Future pre-experiment training with older adults can give participants more time to learn the haptic signals. This approach aims to enhance data reliability and plausibility. This approach has been used in studies by *Garcia A. et al.* [23], *Wachaja et al.* [17] and *Barontini et al.* [24].

According to Fig. 6, in terms of intuitiveness, 100% of the participants preferred the VF, 85% participants agreed that the CF method was intuitive and that value was 80% for the SSF method. Regarding ease of use, 85% of the participants agreed with CF, 100% with SSF, and 95% with VF. Regarding comfort in perceiving haptic signals, all participants were satisfied with VF and CF methods, but in the SSF 20% of the participants disagreed. The lack of comfort experienced with the SSF could be attributed to the handlebar's design, i.e., the low engagement of the skin-stretch ring, which hindered its functioning during the experiment. It can be seen that CF was the participants' preferred method of haptic feedback in this study, followed by the VF. Only SSF makes participants uncomfortable, whereas CF does not because CF employs two feedback strategies from VF besides the four feedback strategies from SSF. This combination may have assisted participants in reducing the discomfort caused by the handlebar design issue. All participants found the haptic handle to be very useful in guiding them, and no one felt that the training on the interpretation of haptic feedback methods before the start of the experiment was insufficient.

The p-value based on the Mann-Whitney U-test showed no significant difference between the three groups. That means the feedback methods do not affect intuitiveness, comfort or ease of use. Due to the lack of significant difference in the intuitiveness between the feedback methods, it is possible to say that the haptic handlebar can provide participants with intuitive directional cues, with an average score of 3.2/4. The rating of these three aspects depends entirely on the subjective judgement of the participant, as people have different abilities to perceive haptic signals [25].

The results from the qualitative assessment established a baseline for how people preferred the feedback methods. However, the applicability of the findings to the older population is unknown and still needs to be verified through more experiments.

VI. CONCLUSION AND FUTURE REMARKS

In this study, a haptic interface integrated into a rollator is introduced to investigate the natural interaction between adults and a walker with the navigation guidance it offers.

Building upon prior research by *Sánchez et al*, the walker's handle was redesigned, incorporating more sensors and actuators [16]. These enhancements facilitate the delivery of haptic feedback, giving users intuitive directional cues to assist them in reaching their desired destinations.

Ten participants were recruited for this study to interact with the haptic handlebar. The experimental data revealed that the skin-stretch feedback method outperformed the other two feedback techniques in effectively communicating navigational cues to participants. The combined feedback exhibited a high performance, with the fastest walking speed. Nevertheless, insights from the questionnaire data indicated that the participants favoured the combined input and vibratory feedback. It was unanimous among all participants that haptic handlebars deliver intuitive navigation guidance.

This study has demonstrated the capacity of haptic interfaces to offer an intuitive experience when receiving navigation guidance. Nonetheless, it is crucial to acknowledge certain limitations within this study. Notably, the absence of experimentation among older adults restricts the direct extrapolation of our findings to this demographic. Furthermore, the design issue of the handlebar not only impacted the participants' overall experience but also introduced potential inconsistencies in the reliability of the experimental data.

Our efforts will be dedicated to addressing the existing design limitations of the handlebar and expanding our participant pool to include older adults. To overcome the mechanical constraints, integrating a higher-torque servo mechanism will be explored, which would facilitate the rotation of the skin-stretch ring. This adjustment alleviates user concerns about inadvertently damaging the handlebar while utilizing the skin-stretch ring. This responds to the feedback obtained through open-ended questions in our questionnaire.

The long-term goal of this work is to ultimately integrate a diverse array of haptic feedback methods into the haptic handlebar to determine the optimal combination that caters to individual preferences and perceptual abilities. Recognizing that individuals possess varying capacities to perceive distinct haptic feedback techniques, the combination of multiple methods holds the potential to render the haptic handlebar accessible and adaptable to a broader spectrum of users.

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