Haptic Human-Robot Collaboration for Walker-Assisted Navigation based on Admittance Controllers

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***Abstract*—In recent years, advances in robotics and the constant growth of gait-related pathologies led to the development of different assistive devices. Smart walkers provide natural and intuitive strategies for gait assistance, such as path-following and guidance. Although these functionalities usually employ shared control approaches, the users' level of participation has yet to be assessed. This work presents the implementation of three modulation strategies for assisted navigation tasks. A path-following algorithm and a set of admittance-based controllers modulate the control authority between the user and the device. A group of 20 healthy subjects formed the validation group. Results showed a kinematic estimation error of 0.13 m for the strategy that shared the control authority with the user. Statistical tests found significant differences regarding the naturalness of the proposed approach (p-value of 0.00587).**

***Index Terms*—Human-Robot Collaboration, Haptics and Haptic Interfaces, Physically Assistive Devices, Rehabilitation Robotics**

I. INTRODUCTION

MOBILITY impaired populations experienced significant and constant growth (i.e., 15% of the world's population) in recent years [1]. Some clinical findings suggest that coexisting health conditions, such as neurological pathologies and old age, could increase the risk factors of long-term disability and decrease individuals' autonomy in activities of daily living [2]. Therefore, there is a global need to propose new solutions and strategies for rehabilitating and assisting people with mobility disabilities [3].

Robotic walkers are a rehabilitation technology equipped with sensory interfaces and actuators to provide physical and cognitive assistance during walking [4]. Also, these devices provide guidance and navigation assistance for a wide range of users with perception and physical impairments [5]. Although existing approaches effectively assist users' navigation, some only rely on feedback strategies that leave the complete control authority to the user [5], [6], [7]. Other approaches do not consider users' intentions or merge them with additional control algorithms [3], [4], [8], [9], [10].

These applications are within the concept of human-robot collaboration (HRC) [11]. For instance, haptic feedback strategies confront the user's intentions with the robot's advice to find a suitable action [12]. These strategies provide remote control and can teach motor skills, e.g., in medical applications [13], [14]. Haptic feedback is effective in physical rehabilitation to enhance user performance, provide compliance, and improve assistance capabilities during cooperative tasks [15], [16].

Strategies for HRC in robotic walkers involve admittance controllers [3], [4]. These controllers enable natural and comfortable interaction during gait [4], [17], [18] by modelling the robotic walker as a dynamic system that provides the user with a sensation of haptic interaction [4]. Guidance and assisted navigation features are also included in robotic walkers [19], [20], [21]. These features provide safety while guiding the users through complex and dynamic environments [3].

Some approaches provide shared control by using feedback to actively involve the user in guidance tasks [20]. Strategies based on haptic, visual, mechanic and auditory stimuli provide shared navigation [5], [20], [22], [23]. However, there is still lacking the qualitative assessment of interaction strategies providing natural and intuitive shared control during path-following tasks. Literature also suggests that motivation and involvement of the user are essential to warrant success and effective user performance in these tasks [24]. Therefore, applications of the HRC concept in robotic walkers lack evaluations where the level of user involvement varies, from the user with complete control of the robot to those where the user has full assistance.

This work describes three strategies for haptic feedback during guidance with a smart walker. The strategies offer different levels of control authority between the robot and the user. The experiments assessed the performance and perception of a group of healthy users to compare the strategies. The main contributions are: (1) the design and implementation of a shared haptic strategy that modulates the level of participation of the users by combining their interaction forces with virtually generated ones, (2) the quantitative comparison of such a strategy with existing approaches, and (3) the qualitative assessment of users' perception while using different haptic strategies.

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Fig. 1: Illustration of the *UFES Smart Walker*.

II. Materials and Methods

A. Robotic Platform

The *UFES Smart Walker*, developed at the UFES, Brazil, was used in this study. Figure 1 shows the platform, its sensors and actuation interfaces [4].

B. Multimodal Interface for Guidance: Case Study

This work proposes three strategies for guiding purposes, where the control authority is modulated between the user and the controller. Each strategy addresses a different level of user involvement through several feedback techniques. In all the strategies the linear speed of the robotic walker is solely controlled by the user and only allowed if the user is leaning on the handlebars [3].

1) User's Intention Detector: The y-axis signals (i.e., impulse signals) are used to obtain the applied force (F) and torque (τ) by the user as proposed by [4]. These signals are pre-processed to remove gait-related components with Fourier Linear Combiner filters as described in [18]. The dynamic mass-damper first order system from Eq. 1 generates the linear velocity $\nu_c(t)$ from the exerted force $F(t)$. m_ν represents a virtual mass and b_ν is the damping ratio. The torque τ is used to obtain the reference angular velocity for the smart walker. The angular velocity $\omega_c(t)$ is calculated as shown in Eq. 2. m_ω represents a virtual mass, and b_ω is the damping ratio. The linear and angular accelerations $\dot{\nu}(t)$, $\dot{\omega}(t)$ were calculated using the current and previous value of the speeds, and the sampling time.

$$\nu_c(t) = \frac{F(t) - m_\nu \dot{\nu}(t)}{b_\nu}, \tag{1}$$

$$\omega_c(t) = \frac{\tau(t) - m_\omega \dot{\omega}(t)}{b_\omega}. \tag{2}$$

Eq. 1 generates the linear speed, but the feedback strategies do not modify it. However, the angular velocity shown in Eq. 2 is subsequently changed. The following values were used: $m_\nu = 3$, $m_\omega = 5$, $b_\nu = 10$, and $b_\omega = 20$.

2) Path Following Controller: The guidance task aims to take the user through the desired path consisting of predetermined poses or goals. This work implements the path-following controller proposed by Andaluz *et al.* to obtain the reference orientation of the robotic walker [25]. The robot's point of interest is in the middle of the rear wheels. The closed-loop equation is:

$$\begin{bmatrix} \dot{x}_D \\ \dot{y}_D \end{bmatrix} = \begin{bmatrix} \nu_r cos\theta_p + l_x tanh\left(\frac{k_x}{l_x}\tilde{x}\right) \\ \nu_r sin\theta_p + l_y tanh\left(\frac{k_y}{l_y}\tilde{y}\right) \end{bmatrix} \tag{3}$$

ν_r is the magnitude of the desired velocity on the path; θ_p is the reference orientation of the path, defined by the tangent of the nearest point to the path; l_x and l_y determine the saturation limits of the position error; k_x and k_y are constant gains that establish the linear zone of the position error, and $\tilde{x}$ and $\tilde{y}$ are the position errors of the smart walker to the path [4]. These constants were experimentally tuned to ensure safe and natural behaviour. Employing the orthogonal vectors $\dot{x}_D$ and $\dot{y}_D$, it is possible to estimate the desired orientation θ_d, using the four-quadrant inverse tangent as $\theta_d = atan2\left(\dot{y}_D/\dot{x}_D\right)$. This information is used to estimate the orientation error $\tilde{\theta}$ between the path and the smart walker orientation θ, as $\tilde{\theta} = \theta_d - \theta$. This controller has proven to be stable by [25]. The following values were used: $\nu_r = 0.3$, $l_x = l_y = 3$, $k_x = k_y = 0.3$.

3) Modulation Strategies: The intention detector module outputs the force and torque exerted on the forearm support, and the linear and angular velocities associated with the user's intention. These variables are inputs for three strategies to modulate the haptic feedback for a path-following task. These strategies can also modify the robotic walker's control authority by changing the user involvement in the task.

- **Shared Modulation Strategy**: This work proposes a new strategy that combines virtual forces with the user torque to provide haptic feedback during guidance, as follows:

$$F_1(t) = k(1 + tanh(\tilde{\theta})), \tag{4}$$

$$F_2(t) = k(1 - tanh(\tilde{\theta})), \tag{5}$$

These forces are used to generate a virtual torque (See Eq. 6, where d is the separation between the forearm supports), which is then combined with the user torque (See Eq. 7).

$$\tau_v(t) = \frac{F_1(t) - F_2(t)}{2} d, \tag{6}$$

$$\tau_s(t) = \tau(t) + \tau_v(t) \tag{7}$$

Finally, the shared torque $\tau_s(t)$ is used to estimate the angular speed of the smart walker, as follows:

$$\omega_c(t) = \frac{\tau_s(t) - m_\omega \dot{\omega}(t)}{b_\omega} \tag{8}$$

Adding the virtual torque τ_v is felt as haptic feedback when the users deviate from the desired path. Moreover, to adjust the effect of the virtual torque, k is used in Eq. 4 and 5. Particularly, the value of k establishes the level of involvement of the user, modifying the influence of the strategy. By using high values of k, the virtual torque will be larger than the torque exerted by the user, especially when the path error is also large. Otherwise, with small values of k, the virtual torque will tend to be very small or almost imperceptible compared to the torque exerted by the user. Thus, adjusting the value of k might be a way to change the user's involvement. In this case, k was set to 25.

- **Assisted Modulation Strategy**: This strategy discards the angular speed [26]. Specifically, virtual torques are generated to guide the user along the desired path. Such torque is calculated through the two virtual forces that employ the orientation error as spatial information to set its values (See Eq. 4 and 5). As described above, the virtual torque is calculated as shown in Eq. 6 and the angular speed is generated as shown in Eq. 9 [26].

$$\omega_\nu = \frac{\tau_\nu(t) - m_\omega \dot{\omega}(t)}{b_\omega}. \quad (9)$$

Eq. 9 is similar to Eq. 2, where the mass and damping parameters must be tuned to guarantee a natural and compliant behaviour. Although the user torque is not considered, this should not be interpreted as a restriction or drawback. If the user's intention differs from the desired path, the haptic feedback indicates that it is a wrong decision, and thus, the user is guided through the path.

- **Dynamic Modulation Strategy**: This strategy is based on adjusting the damping parameter of the admittance controller equation to generate a hard-driving sensation when the user deviates from the desired path. This strategy was previously presented in another work of the authors [4]. However, a simplified version is used here. The values of the masses m_ν and m_ω are left constant. The damping ratios b_ν and b_ω are modified continuously. This modulation is accomplished using a Gaussian-like function, allowing soft transitions between lighter and more complex navigation, which is suitable for the user experience. The users feel that the smart walker is harder to manoeuvre outside from the desired path. This strategy facilitates the smart walker steering when the orientation error $\tilde{\theta}$ is zero.
This strategy ensures that the value of $b_\omega(t)$ decreases when the user tries to correct the orientation error. However, when the user deviates from the desired path, the value of $b_\omega(t)$ increases, implicating that the user has to apply more effort to keep turning. This strategy promotes decision-making processes in the user, as the control authority is set to the user.

The first strategy (i.e., shared modulation) shares the control authority between the users and the smart walker by generating virtual torques when they deviate from the path. The second strategy (i.e., assisted modulation) leaves the majority of the control authority on the smart walker, as the users only control the linear velocity of the task. Finally, the third strategy also provides haptic information employing modifications of the dynamic behaviour of the smart walker. Regarding the stability of the strategies, the use of mass-damper systems (Eq. 1, 2) allows to render slow velocities on the walker. Also, the *tanh* functions in Eq. 4, 5 saturate the virtual forces to prevent very large values.

C. Experimental Setup

1) Participant Recruitment: Healthy subjects participated in the study. The ethics committee previously approved the study, and all participants read and signed the informed consent document. The validation group was conformed of 20 volunteers without gait assistance requirements or cognitive disorders (16 males, 4 females, 31.1 ± 6.7 y.o., 1.71 ± 0.09 m, 72.9 ± 12.1 kg).

2) Session Procedure: The sessions took place at the UFES, and each user was asked to attend one session. Each session consisted of 9 trials divided into 3 trials under each strategy. Three reference paths were used during the three trials corresponding to each strategy. A path with a left turn, a path with a right turn and a path composed of the previous paths were used. The paths were not marked on the ground and the users were only informed about the turning direction. The volunteers were briefly instructed in the behaviour of each modulation strategy. At the end of each strategy, the volunteers were asked to fill out a usability questionnaire.

3) Quantitative Assessment: To measure the users' performance during the trials, the *Kinematic Estimation Error (KTE)* was used [4]. This feature compares the achieved path against the predetermined path. Moreover, to analyse the physical interaction between the users and the walker, several kinematic features were recorded. For each feature, the maximum value, the mean value and the standard deviation of all tests were estimated. To assess the existence of statistically significant differences, Shapiro-Wilk test normality tests were first performed. In the case of obtaining parametric data, the one-way analysis of variance (ANOVA) for repeated measurements was proposed. The Friedman test was proposed for non-parametric data. Finally, the Bonferroni posthoc test was performed for parametric data, and the Conover test with Bonferroni correction was used for non-parametric data.

4) Qualitative Concepts and Assessment: A questionnaire based on previous qualitative assessments of smart walkers [3] and UTAUT-like surveys [27] was designed. The following adjectives were assumed: (1) *intuitive* means easy to understand, (2) *comfortable* means physical easiness and enjoyable interaction, (3) users *involvement* means active consideration of users' intention by the robot, (4) *natural* refers to simple communication and cooperation between the user and the robot. To evaluate different qualitative aspects, six categories were established: (1) Facilitating Conditions (FC) to assess the experience of the user with assistive and rehabilitation devices, (2) System Usability (SU) to identify the ease of use, intuitiveness, perceived safety, and acceptance of the feedback strategies, (3) Control Authority Perception (CP) to evaluate whether the users felt they had the control of the task or the robot had it, (4) Modulation Naturalness (MN) to assess the ability of the feedback strategies to provide a natural experience, (5) Participation Preference (PP) to understand if the user prefers to participate in the control of the task actively, and (6) Interaction Perception (IP) to identify if the user had a natural, intuitive or stressful interaction.

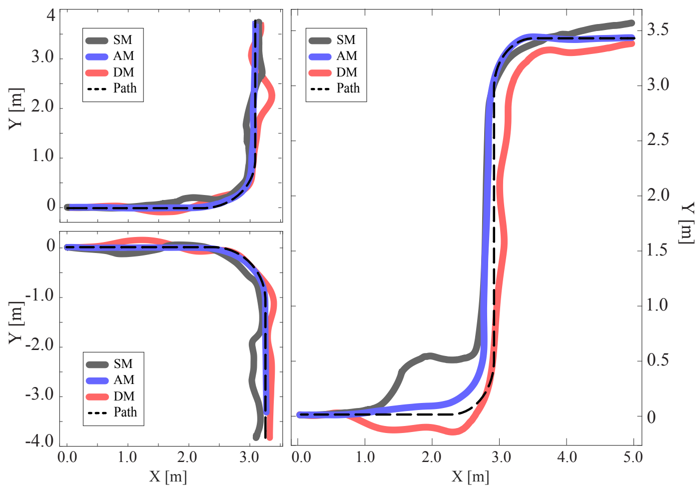

Fig. 2: Path following task example for one subject.

Except for the first category, all questions were designed to be answered using a 5-point Likert scale between *completely disagreed* and *completely agreed*. The answers were compared using a Mann-Whitney-Wilcoxon (MWW) test to assess the existence of significant differences.

III. Results and Discussion

Data were collected from a total of 180 tests. All tests were entirely conducted and no collisions occurred.

A. Quantitative Results

As an illustration of the performance of the different modulation strategies and the paths' geometry, Figure 2 shows the recorded positions of the walker comparing them against the proposed paths for one subject.

1) Kinematic Estimation Error (KTE): Using the position data and the path information registered during the trials, the KTE was calculated. Specifically, Figure 3 shows the mean and standard deviation of the KTE for all the participants. Each data group corresponds to the paths used in the experiments, and the bars describe the mean value of the KTE for the three modulation strategies.

Regarding KTE, the SM strategy was always better than the DM strategy. This might indicate that the users found it easier to interact with the SM strategy. Remarkably, this strategy naturally induced the users to the path direction, using a virtual torque without representing any risk for them. The AM strategy presented the lowest KTE as expected. With this strategy, the user could not deviate from the path; thus it was strictly followed. This is important if accuracy during navigation is necessary. It should be noted that the KTE for the AM strategy is not zero, since the position of the smart walker was compared to a path goal that was always ahead. The DM strategy presented the highest KTE for each path, indicating that the interaction between the user and the robotic walker might be less intuitive (i.e., difficult to understand). Moreover, given that the users had to find the correct orientation, they moved from left to right, and thus they were not always on the desired path.

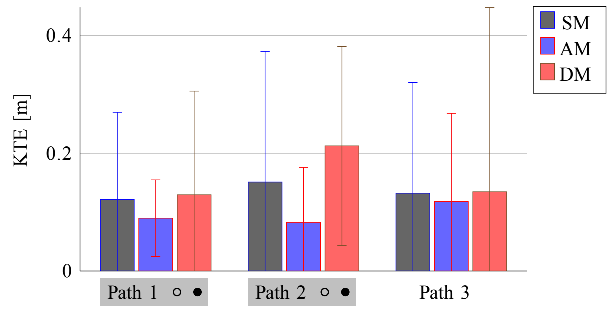

Fig. 3: Kinematic Estimation Error (KTE). Highlighted paths exhibited significant differences. ○ differences between AM and DM. ● differences between AM and SM.

The Friedman tests found differences between the first and second paths. Additionally, post hoc tests indicated that the AM strategy presented differences from the DM and SM strategies. No differences were found for the third and more complex path. This suggests that all the strategies were effective at guidance. This outcome was expected, as the third path was intended to homogenise the trials.

2) Kinematic Interaction: Table I summarises several kinematic and interaction features during the third path among the different modulation strategies. Table II shows the obtained p-values with the Conover posthoc test. No significant differences were found for the Mean Angular Speed and the Max./Mean Orientation Error. The Conover posthoc tests showed significant differences for all the remaining features between the AM and the DM. Between the SM and the DM, only the Max. and Mean Distance features were not found to be statistically different. Between the AM and the SM, only the Mean Linear Speed, the Mean Force and the Duration features were not found to be statistically different. These results suggest that the SM and the AM strategies allowed higher velocities during the trials. This behaviour might be supported by the fact that these strategies were easier to understand, and thus a more comfortable experience was achieved. Regarding the angular speed, the higher values were obtained under the SM strategy as it allowed more deviations from the path. Comparing the dynamic modulation (DM) strategy with the other strategies, significant differences were consistently found for all the features related to the linear and angular speed. This is supported by the fact that the SM and AM strategies were based on virtual torques, while the DM strategy was based on modifying the dynamics of the device.

Regarding the physical interaction with the robotic walker, the maximum user's force value was obtained for the AM strategy. In contrast, the maximum user's torque value was obtained for the SM strategy. It is worth pointing out that the force values were higher under the AM strategy, probably because users felt more confident, and thus their impulse forces were greater. Regarding the mean force, no significant differences were found concerning the SM strategy, presumably because this strategy also provided confidence to users. As expected, the highest torque values were found under the SM and DM strategies, mainly because these strategies allowed the user to drift out of the path. In statistical terms, significant differences were found between the SM and DM

Feature	SM	AM	DM	Friedman p-value
Max. Linear Speed [m/s]	0.37	0.36	0.33	$2.2\text{x}10^{-6}$
Mean Linear Speed [m/s]	0.15±0.11	0.15±0.11	0.08±0.08	$2.2\text{x}10^{-6}$
Max. Angular Speed [rad/s]	0.85	0.49	0.42	$3.3\text{x}10^{-7}$
Mean Angular Speed [rad/s]	-0.01±0.18	-0.01±0.14	0.01±0.11	0.1956
Max. Force [N]	20.19	24.60	21.58	0.0021
Mean Force [N]	2.71±3.60	2.77±3.88	4.51±4.89	0.0003
Max. Torque [N.m]	36.27	14.75	25.68	$7.0\text{x}10^{-8}$
Mean Torque [N.m]	-0.81±6.17	0.95±0.81	0.52±4.92	0.0001
Max. Orientation Error [rad]	3.01	2.39	3.12	0.3311
Mean Orientation Error [rad]	-0.06±0.26	-0.01±0.28	0.04±0.55	0.0799
Max. Distance [m]	7.35	7.56	8.01	0.0061
Mean Distance [m]	7.05±0.17	7.11±0.73	6.39±1.35	0.0061
Max. Duration [s]	97.04	72.18	100.36	$2.2\text{x}10^{-6}$
Mean Duration [s]	48.67±13.88	46.78±8.6	72.73±11.55	$2.2\text{x}10^{-6}$

TABLE I: Kinematic and interaction data during trials. Highlighted parameters were found to be statistically different using Friedman tests.

Feature	SM - AM	SM - DM	AM - DM
Max. Linear Speed	$1.7\text{x}10^{-6}$	$2\text{x}10^{-16}$	$1.3\text{x}10^{-12}$
Mean Linear Speed	0.1	$1.8\text{x}10^{-15}$	$2\text{x}10^{-16}$
Max. Angular Speed	$2\text{x}10^{-16}$	$2\text{x}10^{-16}$	0.00058
Max. Force	0.03	$7.3\text{x}10^{-11}$	$1.9\text{x}10^{-7}$
Mean Force	0.2	$3\text{x}10^{-10}$	$1.9\text{x}10^{-12}$
Max. Torque	$2\text{x}10^{-16}$	$2.3\text{x}10^{-9}$	$1.2\text{x}10^{-15}$
Mean Torque	$1.6\text{x}10^{-14}$	0.0043	$9.9\text{x}10^{-11}$
Max. Distance	$1.2\text{x}10^{-6}$	0.1	$1.7\text{x}10^{-9}$
Mean Distance	$1.2\text{x}10^{-6}$	0.1	$1.7\text{x}10^{-9}$
Max. Duration	0.1	$1.8\text{x}10^{-15}$	$2\text{x}10^{-16}$
Mean Duration	0.1	$1.8\text{x}10^{-15}$	$2\text{x}10^{-16}$

TABLE II: Obtained p-values after pairwise comparisons using the Conover post-hoc. Highlighted parameters were found to be statistically different.

strategies, given that the torque-sharing behaviour was completely different between them. Similarly, the AM and DM strategies presented significant differences for all the values related to force and torque. This is caused by the behaviour of the AM strategy, where the user's torque is not used and the dynamic parameters are left constant.

Regarding the orientation error $\tilde{\theta}$ no significant differences were found. This might indicate that the trials were considerably homogeneous among them. Significant differences were found for distance and duration features. The deviations allowed by the SM and DM led to different travelled distances. Regarding the duration of the trials, similar outcomes were obtained with the SM and AM strategies, while under the DM strategy, the trials were generally longer.

B. Qualitative Results

Regarding the answers of the FC category, 96.7% of the subjects *never* use assistive devices, and 68.3% of the subjects *never* use robotic assistive devices. The 63.3% of the subjects classified their knowledge about rehabilitation and robotics as *novate* or *intermediate*. Thus, these answers classify the volunteers' group as naive users who do not exhibit any bias related to robotic walkers.

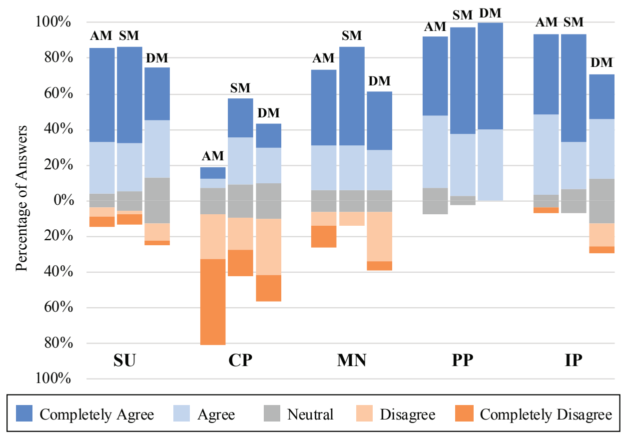

Fig. 4: Answers' distribution of the qualitative questionnaire.

Cat.	SM - AM	SM - DM	AM - DM
SU	0,40517	**0,00001**	**0,00001**
CP	**0,00001**	0,06944	**0,00007**
MN	0,08226	**0,00587**	0,17106
PP	0,08076	0,44038	0,05370
IP	0,12714	**0,00001**	**0,00043**

TABLE III: Mann-Whitney-Wilcoxon test p values. Highlighted values illustrate differences.

The answers' distribution for the following categories of the questionnaire is presented in Figure 4. Table III summarises the results of the MWW test applied in pairs between the modulation strategies and the questionnaire categories.

The System Usability (SU) questions aim to assess the perceived safety, ease of use, and attitude. The answers' distribution for this category was mainly positive, although significant differences were found between the AM and the DM, as well as between the SM and the DM (See Table III). This behaviour might be mainly because users found DM slightly more complicated to use than the other strategies.

Regarding the Control Authority Perception (CP) category, it can be seen that the lowest control perception was given during the AM strategy. The highest control perception took place during the SM strategy. Consequently, significant differences were found between the AM and the SM, as well as between the AM and the DM. However, no differences were found between the SM and the DM strategies. This result may be because these last two strategies allowed a certain degree of control over the path-following task.

The Modulation Naturalness (MN) category determines if the smart walker naturally corrected the user's control actions. The most natural corrections were made during the SM strategy, while the most abrupt corrections occurred during the DM strategy. Moreover, no significant differences were found between the AM and DM strategies. Such an outcome might suggest that the AM strategy is not as natural as the SM strategy. The Participation Preference (PP) exhibited a mostly positive distribution under all the strategies. This means that most users prefer an active participation during the path-following task.

Finally, the Interaction Perception (IP) category evaluates the naturalness and intuitiveness of the strategies. All the strategies presented a mostly positive valence. However, the DM strategy exhibited a smaller distribution. Negative differences between the AM and DM strategies, as well as between the SM and DM strategies were found. This could indicate that the DM category is not intuitive.

IV. Conclusions and Future Work

This work presented the implementation and assessment of several control strategies to provide haptic feedback during path-following tasks with a smart walker. The shared modulation was aimed at sharing the control authority between the user and the smart walker, by generating virtual torques when they deviated from the path. The assisted modulation sought to leave the majority of the control authority on the smart walker, as the users only controlled the linear velocity of the task. Finally, the dynamic modulation was intended to provide haptic feedback employing modifications of the dynamic behaviour of the smart walker.

The assisted modulation strategy maintained and guided the participants across the three paths almost without errors. This strategy did not allow any deviations from the path, as it did not consider the user's torque. Regarding the shared and dynamic strategies, although deviations were allowed, the participants quickly turned back to the proper direction. In addition, a sensation of freedom was induced in the participant with these strategies. Notably, these strategies partially granted control authority to the user, encouraging decision-making processes and cognitive stimuli in the user.

In terms of performance, the users reached higher velocities when they were more comfortable and confident using the robotic walker. Specifically, higher velocities were obtained for the assisted modulation strategy and the shared modulation strategies. However, the mean angular velocity was higher for the dynamic modulation strategy, given that the users felt a sensation of freedom that allowed them to deviate from the path. This might be an advantage in stimulating the users' cognitive system positively.

Regarding acceptance and usability results, most users described positive experiences using the three modulation strategies. However, in terms of participation and interaction perception, the users were more confident under the shared modulation strategy. Such an outcome might be supported by the fact that this strategy was more intuitive and natural. Moreover, the users also stated that they preferred to hold the control authority during the tasks.

Future works will address evaluating the presented strategies in clinical scenarios or with users with mental health issues, such as dementia. These studies will also be focused on assessing the cognitive load induced on the user by the strategies. The shared modulation (SM) strategy can render different levels of users' involvement (i.e., adjusting k value), thus studies will be focused on assessing them. Upcoming work will also target combining these strategies with autonomous navigation modules in dynamic environments. Other robotic fields, such as surgical guidance, could exploit the proposed controllers for feedback purposes.

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