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SWADAPT2: benefits of a collision avoidance assistance for powered wheelchair users in driving difficulty

Bastien Fraudet^a, Emilie Leblong^a, Patrice Piette^a, Benoît Nicolas^a, Louise Devigne^b, Marie Babel^b, François Pasteau^b, François Routhier^{c,d} and Philippe Gallien^a

^aPôle MPR St Hélier, Rennes Cedex, France; ^bInstitut National des Sciences Appliquées de Rennes – CNRS, Rennes, France; ^cDepartment of Rehabilitation, Université Laval, Québec, Canada; ^dCentre for interdisciplinary research in rehabilitation and social integration, Centre intégré universitaire de santé et services de sociaux de la Capitale-Nationale, Québec, Canada
CONTACT Bastien Fraudet - bastien.fraudet@pole-sthelier.com

ABSTRACT

Purpose: In France, tens of thousands of people use a wheelchair. Driving powered wheelchairs (PWCs) present risks for users and their families. The risk of collision in PWC driver increases with severity of disability and may reduce their independence to drive. The European ADAPT project has developed a robotic assistance add-on for PWCs to prevent collisions and improve their driving performance.

Materials and methods: The aim of the SWADAPT2 study is to assess the benefit of this robotic assistance add-on arranged on a Standard Quickie Salsa M2 PWC in a population of PWC drivers with neurological disorders and driving difficulties. Eighteen (18) participants tested the system on three circuits of increasing difficulty, with and without the robotic assistance add-on.

Results: The benefit of the robotic assistance add-on was important especially on the more difficult circuits without impacting cognitive load or driving speed. The number of collisions was significantly reduced when using robotic assistance add-on from 2.16 to 0.36 on circuit 2 ($p = 0.009$) and from 7.3 to 1.33 on circuit 3 ($p = 0.0009$). Task load demand was not increased with the assistance.

Conclusion: Finally, this system seems to be indicated to assist and improve driving safety for PWC drivers in driving difficulty. Evaluation was performed in controlled environments; therefore, further evaluation in real-world scenarios is needed to reach technology readiness.

IMPLICATION FOR REHABILITATION

This device is an effective technology to avoid collisions, especially for patients with neurological disorders in difficulty of driving. Several use cases can be considered: the equipment of drivers who are losing driving ability due to age evolution of their pathology, or anxiety; the equipment of users in driving training with difficulties, in order to facilitate access to users who are currently unable to drive.

KEYWORDS

Smart wheelchair; rehabilitation; neurological diseases

Introduction

The World Health Organization (2008) estimated that about 65 million people use wheelchairs (powered or manual), which represents about 1% of the world population [1]. As reported by Kokosy et al. [2], the prevalence of wheelchair users is increasing in Western countries, estimated at 60–200 per 10,000. This prevalence is 92 per 10,000 in USA [3], and 90 per 10,000 in Canada [of which 14.8% are powered wheelchairs (PWCs)] [4]. In Europe, prevalence is 6.4 per 10,000 inhabitants in France [5], and 200 for 10,000 in Great Britain [6].

While the use of a wheelchair improves the quality of life of the person and their family, it also exposes them to certain risks. In 2006, 100,000 accidents involving wheelchair users were recorded in the USA [7]. Edwards reported that the yearly accident rate of WC users in Australia was 21% [8]. In the Chen study in Taiwan, 54.7% of subjects said they had experienced at least one accident in the past three years [9]. Tips and falls are the leading mechanisms of related injury, but accidental

contacts with an immovable or mobile object or being represent 7% of the wheelchair-related accidents. The risk of collision accidents is one of the main problems reported due to environmental (obstacles, road quality) and human (difficulties linked to disability, or inappropriate behaviour) [10,11] factors, which can have major consequences for health and social participation [12,13].

PWCs are essential technical aids for many individuals, allowing them to maintain independence of movement and contribute to a satisfactory quality of life [14–16]. But the risk of collision may increase with the level of disability. It can restrict its use thus resulting in limited mobility which further impacts daily autonomy and quality of life [17–20]. In this context, minimising



Figure 1 : standard conditions for people with driving difficulties reduces the number of collisions, without impacting driving speed or mental workload.

the risk of collision *via* navigational assistance would allow people who are not eligible to use a PWC to have access to this option, or PWC users who have difficulties due to their disability to continue using their wheelchair. Patients suffering from visual disorders, cognitive slowness, or significant functional limb impairment may benefit from such a solution.

For several years, PWC navigation assistance using environmental sensors has been studied extensively by many laboratories, whether involving ultrasonic sensors [21–23], infrared sensors [24,25], cameras [26], or even lasers [27,28]. However, few solutions have been brought to market especially because smart-wheelchairs are considered as a “ niche market” [29]. There is a broad range of disabilities who can benefit from navigation assistance but several reasons limit their development as sensor’s cost, lack of standard communication with commercial PWC, lack of clinical evidence, and clinician and user’s acceptance [30]. Most of the experiments were conducted on people without disabilities. Moreover, most of publications with PWC users included a limited number of participants [10,25,30,31].

Only a few devices are available on the market. Braze and Smile Smart System are obstacle-warning systems [32,33]. Luci is the only one including obstacle detection and collision avoidance. These devices are perceived as simple and useful and reduce the mental load when driving PWCs [29,34]. However, these solutions require the driver to process the information and then adjust his trajectory.

Under the scope of the ADAPT project (*Assistive Devices for empowering disAbled People through robotic Technologies*) [35] a robotic assistance add-on capable of handling positive obstacles (collision avoidance module) was developed. The module is a semi-autonomous driving assistance system, with the module activated the PWC will stop on a frontal arrival in front of an obstacle. In the event of an angled arrival the PWC will autonomously circumvent the obstacle by skirting it. The SWADAPT1 study [25] validated the feasibility, acceptability, safety and benefits of the anti-collision module in patient who were regular wheelchair users without any difficulty in using PWCs in daily life. Moreover, the use of robotic assistance add-on significantly reduced the risk of collision on the most complex circuit. In this second stage of the project (SWADAPT2), our aim was to evaluate the benefit of this robotic assistance add-on module for PWC users with driving difficulties comparing the use of the wheelchair with and without the detection system on the three circuits. We hypothesis that the use of robotic assistance add-on module in assessment days, 7 d apart, requiring them to navigate a circuit of increasing difficulty over a period of 15 d. The circuits were the ones that had been designed and used in the ADAPT project, described in the SWADAPT1 study [25]. The scenarios of the three circuits were defined based on a survey (publication in progress) of 366

professionals who evaluated the level of difficulty of a list of 31 driving tasks synthesising data from different assessments and standardised programs (PIDA, WST and WSP) and the experience of professionals. The 3 levels of the 3 circuits were inspired by these data to include tasks corresponding to increasing difficulty (Table 1). Each circuit corresponded to a difficulty level, i.e., C1 low, C2 moderate, C3 high difficulty (Figure 2). Each assessment day comprised an initial interview (demographic questionnaire, presentation of the system), the time to discover the circuit, the time to test the circuit, and time for an assessment after each randomisation mode. The order according to which participants were tested on the circuit (with or without the assistance module) was determined randomly on each assessment day. Each test run on the circuits was preceded by five minutes of hands-on time with the PWC used for the test. Each circuit was tested three times consecutively in one or other of the modes (with and without activation of the robotic assistance add-on) whose order depended on the randomisation. A 30-min washout period between each mode corresponding to the completion of the questionnaires was performed. In total, each participant made 18 test runs; six on each circuit and three in each mode.

Table 1. The different tasks included in each circuit.

Circuit	Task description
1	Wide corridor (2.5 m) Forward Wide turn U-turn on site Reverse
2	Fixed obstacle on the ground to be circumvented Low slope (5°) to go down and up Wide corridor/wide doorway Fixed obstacle on the ground to cross Low and moderate slope (5° and 10°) to go down and up
3	Fixed obstacle in height Emergency stop Stop with precision Walk along a wall Narrow corridor (1.5 m) Table: setting up Double stain Elevator simulation: forward entry and reverse exit Restricted space Moving obstacle to bypass

Outcome measures

The primary outcome measure was the number of collisions reported during each run. A collision was defined as any physical contact between any part of the PWC and any part of the circuit. Two occupational therapists independently assessed (by direct observation) the number of collisions during each run on the three circuits. They were unaware of which mode was being used. In the event of disagreement between the two observers, the data retained were the data with the highest score. The outcome measure “number of collisions” retained for each experimental

condition (with and without activation of the robotic assistance add-on) was the mean number of collisions from three runs of each of the circuits.

The secondary outcome measures were:

- the mean speed calculated over the three runs in each mode on each circuit (mean of the 3 runs);
- Task load demand and mental demand by the raw NASA Task Load Index (NASA TLX) [36,37] and sub-score.

The raw NASA-TLX instrument is partitioned into six distinct subscales, namely mental demand, temporal demand, physical demand, performance, effort and frustration. Each of these subscales is assigned a numerical score ranging from 0 to 100. The NASA task load index is computed as the mean of the scores from the six subscales: usability of the add-on assessed via the Usability, Satisfaction and Ease of Use Questionnaire (USE), composed of 30 questions grouped in four dimensions: usefulness (8 items), ease of use (11 items), ease of learning (4 items) and satisfaction (7 items). Each item is measured by a 7-point Likert scale, the score for each dimension is out of 7 [38].

Task load demand and usability were assessed after three runs had been completed in each mode, for each of the three circuits.

Statistical analysis

As each circuit was run three times to obtain the score of collisions and run times, the mean of the three runs was

calculated.

The mean for the number of collisions and time was used to respect the protocol of the first study [25].

The statistical analysis related to these means. The other scores were only assessed at the end of the series of three consecutive tests with or without assistance. Statistical analysis was performed using R studio software, version 4.0.5 (2021), on matched data. Descriptive quantitative data included the mean, standard deviation, median and quartiles. The Shapiro–Wilk test showed that the sample was not normal for the main criterion ($p < 0.0001$).

The Wilcoxon test for matched samples was therefore used to compare the data. For the raw NASA-TLX data no pairwise comparisons were used and no weighted score was calculated. Comparison for condition with/without assistance, were assessed via paired Wilcoxon signed ranks.

Effect sizes were calculated using the Wilcoxon test and confidence intervals by bootstrapping. The significance threshold used was 0.05. The predictability of driving difficulty (WST-Q) on the safety gain of the robotic assistance add-on (difference between the number of collisions with and without assistance) was assessed using a linear regression model.



Figure 2. Evolution of collisions on the 3 circuits (W; with assistance, W/O: without assistance).

A diagram presenting the average number of collisions measured on the 3 circuits C1, C2, C3. These results show that the difference in the number of collisions increases with the difficulty and becomes significant for the second circuit and multiplied by 5 for the C3.

Results

Population

Sixteen participants took part in the study, eight men and eight women with a mean age of 57 ± 13 years. Characteristics of the population are shown in Table 2. Fourteen participants took part in all the three tests on the three circuits. One participant did not complete the third test run on circuits 2 and 3 and one other participant did not complete the third test run on circuit 3 due to fatigue following the driving session.

Number of collisions

The first circuit did not present any major difficulties (driving in a wide corridor in forward direction, turning in a wide space, wide turns) (Table 3, Figure 3). Collisions were only reported in four participants. From the second circuit onwards, the use of assistance significantly reduced collisions from 2.16 (3.73) to 0.36 (0.9) ($p = 0.009$). For circuit 3, the most complex circuit with the maximum number of high-risk situations, 100% of users had collisions but the robotic assistance add-on significantly reduced the number of collisions from 7.30 (8.90) to 1.33 (1.40) ($p = 0.0009$). The effect is large for circuit 2: r value = 0.73, 95% CI [0.56–0.85]; and large for circuit 3: r value = 0.83, 95% CI [0.68–0.88]. We fitted

a linear model to predict “collision gain” with WST-Q score. The model explains a statistically significant and moderate proportion of variance ($p = 0.044$, adj. $R^2 = 0.21$). Within this model, the effect of WST-Q score is statistically significant and negative ($\beta = 0.68$, 95% CI [-1.34–0.02], $p = 0.044$).

Statistical analysis demonstrated none difference concerning efficacy of the assistance regarding hand laterality.

Duration of circuit

No significant differences were reported between the two modes (Table 4, Figure 4). The use of the robotic assistance add-on did not affect the completion time of the run in people with driving difficulties.

Task load demand and mental demand (NASA-TLX and subscore)

Task load demand was moderately high for the three circuits, regardless of the mode (Table 5, Figure 5). The introduction of robotic assistance add-on did not significantly change this task load demand, even if a downward trend was observed for circuits 2 and 3 in the assisted mode.

However, a closer analysis of the NASA sub-scores shows a significant difference of 11.6 points on the mental demand score, in favour of the assistance ($p = 0.05$).

Usability (USE)

Scores were high in the four dimensions demonstrating a good level of usability of the robotic assistance add-on in the context of the experiment, with or without the assistance module and without the module having an impact on the usability of the wheelchair (Table 6).

Discussion

The results obtained in this study are consistent with the data previously reported in the literature. However, while several studies report experiments and assessments with PWC users as part of an assessment of smart wheelchairs, most of these experiments were conducted on people without disabilities [10,30,39–53]. A few publications report case studies of PWC users with a limited number of participants ranging from 1 to 9 people [10,30,39,43, 44,47,54–61]. Only Ju et al. [62], Shiomi [63] and Pellichero et al. [34] have tested their solution on cohorts of more than 10 participants with disabilities. This is one of the first studies involving a cohort of more than 10 participants with disabilities assessing smart wheelchairs. Most of the study population were powered electric wheelchair users with cerebral disabilities, only two participants had spinal cord injuries.

Table 2. Characteristics of the population studied.

Participants	Gender	Age	Pathology	Laterality	Number of items with WST-Q ability score <2
1	Men	68	Stroke	Left	17
2	Women	45	Stroke	Right	11
3	Men	56	Cerebellar syndrome	Left	12
4	Women	32	Severe visual disturbances of unknown central origin	Right	1
5	Men	76	Quadriplegia	Left	14
6	Women	34	Cerebral palsy	Left	15
7	Men	72	Cerebellar syndrome	Right	9
8	Men	43	Quadriplegia	Right	1
9	Women	51	cerebellar syndrome	Right	5
10	Women	62	Stroke	Left	12
11	Women	59	Stroke	Right	6
12	Men	66	Stroke	Right	1
13	Men	73	Stroke	Right	1
14	Women	50	Stroke	Right	11
15	Women	59	Brain injury	Left	1
16	Men	64	Parkinson	Right	3

Table 3. Comparison of the number of collisions on the three circuits between without (W/O) and with (W) assistance, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Circuit	Collision		Wilcox test <i>P</i> value
	Mean (sd) W/O	Mean (sd) W	
C1	0.39 (1.01)	0.06 (0.18)	0.18
C2	2.16 (3.73)	0.36 (0.9)	0.009**
3	7.30 (8.90)	1.33 (1.40)	0.0009***

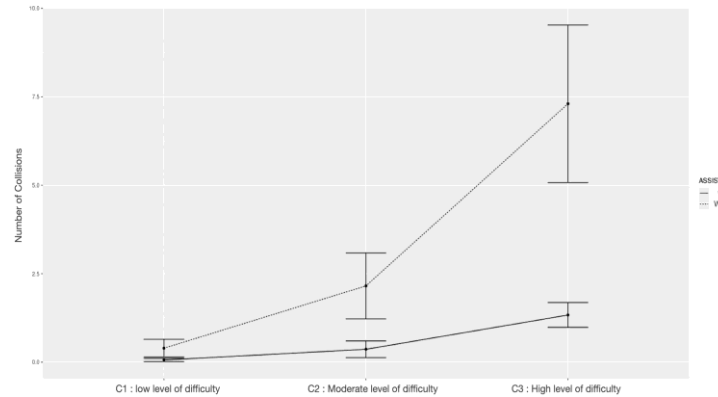


Figure 3. Evolution of running time on the 3 circuits. (W: with assistance, W/O: without assistance).

A diagram presenting the completion time of the course measured on the 3 circuits. The figure shows that the duration increases in the 3 circuits but in an almost parallel way with a difference which remains not significant for the 3 circuits

Table 4. Comparison of time to completion on the three circuits between without (W/O) and with (W) assistance.

Circuit	Time (s)		Wilcoxon test <i>p</i> value
	Mean (sd) W/O	Mean (sd) W	
C1	109.8 (34.7) 95.8	105.5 (30.9) 95.0	0.97
C2	148.4 (84.5) 116.3	149.8 (76.4) 113.5	0.83
C3	264.1 (97.2) 194.6	227.3 (113.9) 234.8	0.13

In the case of brain damage, particularly supra-tentorial damage, cognitive elements often accompany motor difficulties making wheelchair driving more complex due to issues including attention deficit, executive-decision making or visual-spatial issues such as hemispatial neglect. Fatigue is also an important impairment, which can limit daily life activities. Two participants in our trial did not complete the study, because travel to participate in the study was finally too exhausting for them. The system under study is a robotic assistance add-on that does not require cognitive processing by the participant as it corrects the trajectory of the wheelchair automatically without user intervention. This further limits the risk of collision compared to warning systems that require action following the perception of the alert and therefore depend on the user's reaction time, which is often increased in the case of cognitive disorders. Our results tend to show that its effectiveness in preventing collisions does not impact either performance, cognitive load or tiredness as may be the case with other systems based on visual distance mapping [64] or auditory instructions [65]. The robotic assistance add-on studied could reduce this cognitive

load during the most demanding tasks. In addition, the user does not require a learning phase, which can be a lengthy and complex process in the case of cognitive disabilities. It is therefore perfectly suited to the target population with driving difficulties connected to central neurological injuries. Moreover, the regression results seem to show that the greater the driving difficulty, the greater the benefit of the robotic assistance add-on. The robotic assistance add-on is especially useful for drivers with major difficulties.

From a technological perspective, it is important to emphasise the easy interfacing of the system with a commercial PWC. Thus, unlike many driver-assistance solutions proposed in the literature [66], neither the electronics of the chair nor the chassis have been modified for the automation. The proposed solution is therefore completely risk-free and easy to install on wheelchairs using R-net. Further work might be needed to generalise to other power wheelchairs.

In addition, the same PWC, uniquely configured (speed, margins for obstacle avoidance), was used by all participants to avoid any technological bias. Only the control interface was adapted to the abilities and habits of participants (simple joystick adapted as required for either a T-handle or ball control). The standardised configuration used for the study is therefore suboptimal from the perspective of the user: the chair used may differ considerably from the personal chair of the participant (motorisation, settings, finer adjustments). However, the performances achieved by the robotic assistance add-on in this study underline the ease of use, as seen in the USE scores.

Table 5. Comparison for condition with (W) vs without assistance (W/O) for raw NASA-TLX.

Variable	¼ W Mean (sd)	¼ W/O Mean (sd)	¼ p Value Wilcox sum rank
Circuit 1			
Nasa 1	45.62 (29.88)	40.00 (33.38)	0.551
Nasa 2	26.25 (24.46)	33.00 (28.77)	0.521
Nasa 3	21.25 (24.46)	22.67 (25.20)	0.952
Nasa 4	28.12 (20.07)	33.67 (20.39)	0.484
Nasa 5	40.62 (28.16)	37.00 (30.58)	0.750
Nasa 6	20.00 (27.81)	8.33 (28.14)	0.818
NTLI	30.31 (20.02)	28.41 (22.8)	0.999
Circuit 2			
Nasa 1	43.75 (23.63)	42.81 (23.80)	0.999
Nasa 2	28.12 (26.13)	30.62 (24.07)	0.398
Nasa 3	24.06 (20.10)	24.38 (23.37)	0.803
Nasa 4	26.56 (24.68)	24.38 (19.31)	0.999
Nasa 5	38.75 (26.04)	42.81 (24.90)	0.798
Nasa 6	25.31 (29.97)	26.25 (26.80)	0.999
NTLI	30.79 (10.77)	36.07 (11.62)	0.215
Circuit 3			
Nasa 1	40.62 (25.68)	51.88 (29.26)	0.005 ^{***}
Nasa 2	27.81 (24.56)	32.19 (28.46)	0.205
Nasa 3	23.12 (18.15)	28.44 (19.47)	0.538
Nasa 4	31.88 (20.40)	40.00 (18.62)	0.042 ^{**}
Nasa 5	42.50 (26.96)	44.38 (25.81)	0.497
Nasa 6	24.38 (27.32)	22.81 (27.93)	0.877
NTLI	31.62 (18.10)	36.51 (19.57)	0.065

Nasa 1 Mental Demand, Nasa 2 Physical Demand, Nasa 3 Temporal Demand, Nasa 4 Own Performance, Nasa 5 Effort, Nasa 6 Frustration Level, NTLI NASA Task Load Index. Signif. codes: 0 '***', 0.001 '**', 0.01 '*', 0.05 '.' 0.1 '' 1.

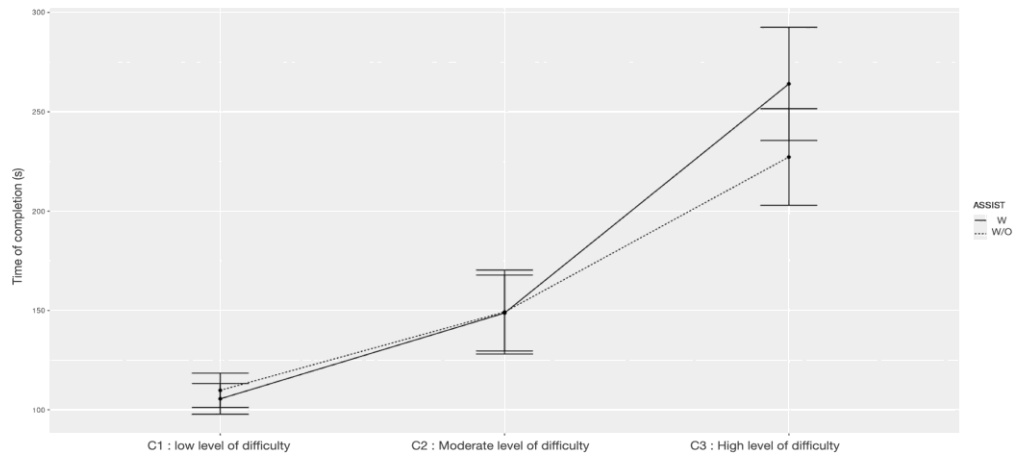


Figure 4. Evolution task load and mental demand on the 3 circuits (W: with assistance, W/O: without assistance).

A diagram presenting the evolution of the mental load through the global score of the NASATLX and its mental demand sub-score. It shows a non-significant tendency that the mental load increases more the difficulty of the circuits for the condition without assistance in comparison with the use of the anti-collision sensors

Table 6. Comparison of USE sub-scores without (W/O) and with (W) assistance.

Circuit	Mean (sd) W/O	Mean (sd) W	Wilcox test p value
Utility			
C1	5.66 (0.90)	5.72 (1.15)	0.70
C2	5.56 (1.28)	5.53 (1.46)	0.81
C3	5.49 (1.18)	5.57 (1.30)	0.87
Facility use			
C1	6.04 (0.84)	6.09 (0.72)	0.90
C2	5.91 (0.75)	6.07 (0.72)	0.15
C3	5.99 (0.85)	6.13 (0.79)	0.63
Facility learning			
C1	6.25 (0.72)	6.20 (0.78)	0.88
C2	6.27 (0.58)	6.23 (0.86)	0.49
C3	6.16 (0.71)	6.33 (0.87)	0.19
Satisfaction			
C1	5.80 (1.13)	6.50 (0.82)	0.59
C2	5.66 (1.04)	5.42 (1.31)	0.16
C3	5.31 (1.75)	5.36 (1.43)	1.00

Finally, as no learning process is required, robotic assistance add-on is transparent to the user: the system is based on an intuitive cooperation between the robotic system and the user. It therefore does not affect the mental load. This is an important issue for the acceptance of any technological assistance.

Concerning limitations, first, the sample size was small and the length of driving experience and disability level varied widely (5 participants only had a single WST item lower than 2 compared to 14 items for other participants) as did the profile of disorders, which makes it difficult to generalise the results to all users with driving difficulties.

Second, a single PWC model was used in the experimental sessions, for standardisation purposes. However, it is well known that driving performance is also linked to the adaptation of the WC to the needs of the participant. The performance achieved may have been biased by this choice.

In addition, the results were obtained under circuit conditions

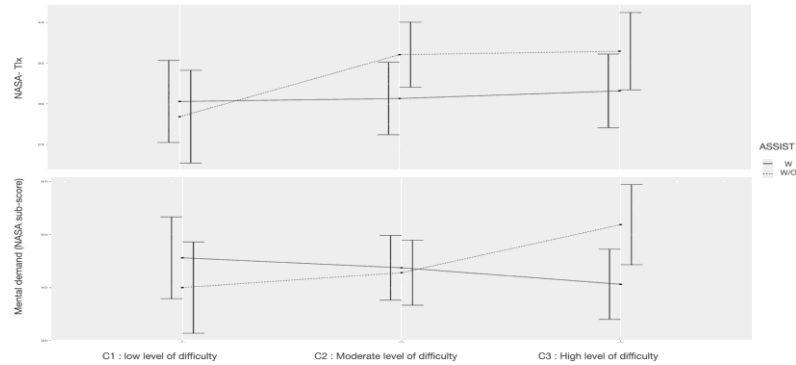


Figure 5. Evolution task load and mental demand on the 3 circuits (W: with assistance, W/O: without assistance).

which, although they tend to reproduce environment-related tasks, are still conditions close to laboratory conditions and do not greatly reflect the reality of the daily lives of users. The transposition of the results into everyday life is still debatable at this stage.

Conclusion

This study demonstrates the value of the robotic assistance add-on in preventing collisions with positive obstacles for PWC users with driving difficulties in controlled situations. Further evaluation in real-world scenarios is needed to reach technology readiness.

In addition, to achieve full mobility autonomy inside and outside, the risks of tipping and falling due to the presence of negative obstacles in urban situations should be considered [28]. Outside of the home, many situations may involve a risk of tipping over (edges of steps, pavements, etc.). Considering negative obstacles is therefore an important additional stage in driving autonomy. The ADAPT project will therefore continue to develop robotic assistance add-on to prevent risks linked to negative obstacles.

Note

1. https://www.legifrance.gouv.fr/codes/section_lc/LEGITEXT000006072665/LEGISCTA000006154978/#LEGISCTA000025457387

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Authors' contributions

The authors cited have all contribute to this trial. MB, FP and LD have participated to technical the development of smart PWC. They all participate to the technical support during the trial. BN, PG and EL participate to the enrolment of the participants. PG and EL participate to the protocol writing. BF participate to the protocol elaboration and coordinate the trial. PP was responsible of statistical analysis. EL, PG, and BF participate to the analysis of the results. BN, PG, MB, PP, FR and BF

participate to the writing and to the reviews of this article.

Ethical approval and consent to participate

This study was approved by the ethics committee *Comité de Protection des Personnes CPP Sud Méditerranée IV* the 11th 2019 (n°2019-A01306-51). This study was registered the 6 October 2020 on ClinicalTrials.gov, ID: NCT04259151 <https://clinicaltrials.gov/ct2/show/NCT04259151?term=gallien&raw=2&rank=6>

ORCID

Bastien Fraudet <http://orcid.org/0000-0003-0472-4738>
 Marie Babel <http://orcid.org/0000-0001-6425-389X>
 François Routhier <http://orcid.org/0000-0002-5458-6233>

Consent for publication

All authors consent to this publication

Availability of data and materials

The dataset uses and analysis during the current study are available from the corresponding author on reasonable request.

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Disclosure statement

The authors declare that they have no competing interests.

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