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Robotic Wheelchairs: Scientific Experimentation or Social Intervention?

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***Abstract*— Research in robotics is becoming an ever more applied science. Roboticists acknowledge the existence of a role for experiments in their research, but whether the results of such experiments provide useful information to the intended industry or profession remains somewhat ambiguous. In this paper, we particularly consider experiments relating to robotic wheelchairs. There are many prototype robotic wheelchairs, but what level of performance must they achieve before being accepted into mainstream society and how do we verify the reliability of such performance? How can researchers evaluate their systems effectively? We compare and contrast the metrics used by medical practitioners to gauge the mobility status of a patient with those that are popularly used in academia to evaluate robotic wheelchair performance. We conclude that to design and execute successful experiments with robotic wheelchairs, researchers must draw not only on the experience of the intended end users, but also on the expertise of the medical practitioners who assess and support the patients in the day–to–day use of their wheelchairs.**

I. INTRODUCTION

Powered wheelchairs play a vital role in bringing independence to the severely mobility–impaired and allow people to get on with their activities of daily living. However, many users have difficulty controlling their wheelchairs, for a variety of different reasons that will be addressed later in this paper. Roboticists aim to provide an all–encompassing solution to many of these problems by introducing "smart" wheelchairs. However, very few smart wheelchairs have ever made it to clinical trials, let alone to the patient for everyday use. To investigate why this might be, we discuss the disparity between experiments that are being carried out by developers of robotic wheelchairs and the assessments of patients that are undertaken by medical practitioners.

We begin this paper by introducing some of the main problems faced by both existing and potential users of powered wheelchairs, before giving an overview of the types of smart chairs that are being developed to overcome these problems. Then we review the types of evaluations roboticists perform to validate such systems. These are compared with the experiments that clinicians run to objectively measure the competency of a patient's wheelchair skills. This leads on to a brief discussion of the wide variety of protocols that exist for prescribing wheelchairs to patients. Drawing upon these findings, we look at how advice from clinicians can be incorporated into the academic evaluation of smart wheelchairs such that the results are meaningful to professionals and end users alike.

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A. Wheelchair users and problems they face

Many people who suffer from mobility–impairments rely on powered wheelchairs to get out and about. In 2000, it was estimated that there were over 11350 electrically powered indoor/outdoor chair (EPIOC) users in the UK alone and this number was growing steadily by over 3500 per year [1]. However, a substantial number of users find it difficult to operate their chairs effectively; this can be due to a variety of physical, perceptive or cognitive impairments [2]. In a study of young people using EPIOCs, Evans *et al.* found common accidents that occurred included "the chair running into people" and "banging into furniture" [3]. In another study, Frank *et al.* reported that over 10% of users had accidents within four months of receiving their EPIOC [4]. This shows that there is a clear need for the development of smart wheelchairs that would empower people with mobility impairments to get on safely with their activities of daily living.

It has also been suggested that providing wheelchairs to infants as early as possible, could enhance both their cognitive and psychosocial development [5]. In the study, Tefft *et al.* present some preliminary results that suggest that a degree of *problem–solving* and *spatial relations* skills are required in order to begin exploring powered mobility. If a smart wheelchair could be driven safely, with lower requirements of such skills, a severely disabled child could become mobility–independent at an earlier age. Consequently we may be able to expedite their cognitive and psychosocial development.

II. SMART WHEELCHAIRS

Several research groups have taken different approaches to helping the user manoeuvre safely. These range from those that offer some low–level collision avoidance, to those that use a high level of autonomy and require relatively little user interaction, as was done by Taha *et al.* [6]. For people with severe physical disabilities, which prevent them from interacting in a conventional manner, Millán *et al.* developed a brain machine interface for powered wheelchairs [7], while Simpson and Levine have carried out preliminary experiments with voice control [8]. Many hybrid systems are also being researched, which switch (sometimes autonomously) between different modes of operation, such as the NavChair [9]. Ding and Cooper present a more comprehensive review of intelligent wheelchairs in [10].

However, just because a researcher is able to create a fully autonomous system for transporting people with mobility impairments, does not mean that this is necessarily what the end user wants. Instead, it has been suggested that a smart wheelchair should assist users only when they are

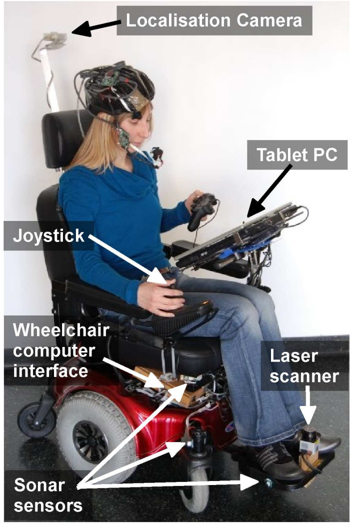

Fig. 1. Global localisation data from the camera is used alongside dynamic sensory data from the laser scanner and sonars to assist the user in performing precise manoeuvres [12].

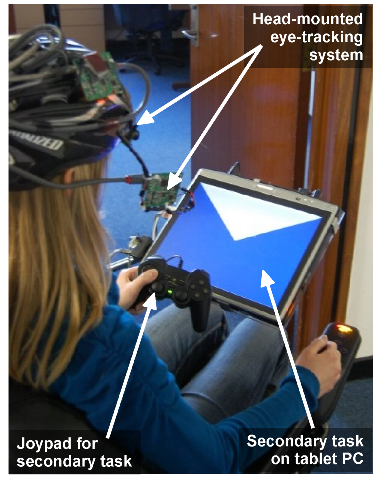

Fig. 2. In our evaluations, we monitored the user's visual attention with a head-mounted eye-tracking system. as they perform standard manoeuvres [13]. We have also monitored the user workload, by administering a secondary task, whilst the participant was simultaneously driving the wheelchair [16].

incapable of manoeuvring safely themselves [11]. We follow this recommendation for our robotic wheelchair (Fig. 1), keeping the control user–initiated and only adapt signals where necessary, e.g. to prevent a collision or to perform a particularly precise manoeuvre [12].

III. ROBOTIC WHEELCHAIR EVALUATIONS

In a UK–based study that examined 174 patients referred to be assessed for the provision of an electrically powered indoor/outdoor chair (EPIOC), 24% were found to be unsuitable candidates [4]. The study found that the most frequent reason for the judgement was that the patient had "inadequate control of the chair" and this was closely followed by "visual inattention or neglect or unable to judge distances". This is why in the evaluations of our wheelchair, we have focussed on human–factors such as their visual attention [13] and manual dexterity [14]. Additionally, whilst wheelchair users are driving, they are often simultaneously interacting with their surroundings or other people. For example, Brandt *et al.* found that 87% of the 111 people surveyed used their wheelchairs to go shopping [15]. Clearly there is a need for divided attention between manoeuvring the wheelchair safely and finding the items on the shelves, so it is important that a patient's ability to share attention between tasks is measured, if they are likely to be performing such tasks. We have performed secondary task experiments to evaluate user workload [16], as shown in Fig. 2 and similar evaluations have been carried out by Parikh *et al.* on their intelligent wheelchair [17].

Tsui *et al.* briefly reviewed some of the performance metrics that have been popularly used to evaluate intelligent wheelchairs [18]. They note a common test used by both robotics researchers evaluating systems [9], [12] and practitioners assessing patients [19] is to check the ability of a driver to navigate through a doorway safely. It is therefore encouraging to see that there is some common ground between the evaluations of robotics researchers and medical practitioners.

However, a problem often faced by robotics researchers is managing to carry out significant experiments with end users. Yanco reports some of the difficulties involved in transferring patients (and their specialist seating requirements) to a prototype intelligent wheelchair [20]. It is not only a time–consuming process, but also one that requires great expertise, so it is desirable to work alongside practitioners wherever possible. To minimise these problems, some research groups take the approach of performing a series of trials with able bodied subjects and correlating the results with a case study of a typical end user [21]. Despite the difficulties, a minority of research groups have successfully managed to complete small clinical trials of robotic wheelchairs. For example, in the PALMA project, Ceres *et al.* conducted trials with five children who had both physical disabilities and cognitive impairments [22].

IV. OBJECTIVE MEASURES OF PATIENT ABILITY

In this section we look at methods in which practitioners can gauge a patient's ability to manoeuvre a wheelchair safely. We note that typically a person's wheelchair skill level is not static, but changes over time, as they become more adept at manoeuvring, or perhaps they deteriorate due to the progression of a degenerative neuromuscular disease [23]. Either way, an initial assessment must be made and this should be followed up at regular intervals, which depend on the nature of the patient's disability.

A. Initial assessment

The Power–Mobility Indoor Driving Assessment provides a measure of a patient's mobility competency in a natural environment [24]. In this test, patients are observed performing typical manoeuvres in the bedroom and bathroom as well as the more commonly evaluated tasks, such as driving through doorways and into elevators. They are scored on an ordinal scale ranging from one to four, according to how well the manoeuvre is executed (1 = unable to complete the task, 4 = task completed smoothly and safely on first attempt). A percentage total is then calculated over all the tasks, which indicates the patient's competency.

An alternative procedure, the Wheelchair Skills Test, was designed by Kirby *et al.* to provide a quantitative measure of a manual wheelchair user's ability to manoeuvre safely and effectively in a controlled environment [25]. Many of the navigational criteria assessed would also be applicable to powered wheelchairs, for example, the ability to perform turning manoeuvres (parallel parking, three–point turns, turning on the spot etc.) and, as previously mentioned in Section III, the ability to negotiate doors. Additional criteria, that are not often discussed by roboticists, but are extremely relevant to enabling the patient to get on with their activities of daily living, are the abilities to reach objects and pick them up, whilst seated in the chair. We suggest it would be beneficial to perform an evaluation of smart wheelchairs that follows the guidelines of the Wheelchair Skills Test, to ensure that intelligent controllers do not interfere with performing activities of daily living. For example, it is conceivable that a collision avoidance system may not allow a user to get close enough to a ledge to pick up an object from that ledge, especially if the user has limited upper–body mobility.

B. *Longer–term monitoring*

A protocol was developed in The Boston Home nursing facility to deal with changes in patients' long–term neuro–degenerative conditions that resulted in a degraded ability to manoeuvre their powered wheelchairs safely [23]. The wheelchair driving assessment team would monitor a patient for a period of 2 weeks, logging wheelchair–related incidents, such as: collisions with objects or people; difficulty in manoeuvring in tight spaces; wheelchair repairs outside of normal maintenance and complaints from other patients. Patients are then assessed in relation to these incidents to determine whether or not they are still capable of driving a powered wheelchair. They are assessed in terms of cognition, vision, medical status, motor skills performance and general level of activity.

In one case study, a patient at the nursing facility was deemed unsuitable for powered mobility, based largely on the deterioration of the ability to manoeuvre precisely or respond to auditory warnings [23]. Problematic scenarios for the patient included driving safely in and out of the elevator, through doorways and around other patients. The staff at the nursing facility had adapted her chair and even fitted visual aids and buzzers, in an effort to allow her to continue driving independently. Such patients would make great candidates for smart wheelchair trials, since it is their last resort in terms of mobility independence.

Determining wheelchair mobility performance is more complicated than simply evaluating how well a user negotiates an obstacle course. A study by Routhier *et al.* shows that the mobility of a patient is affected by factors such as the user's characteristics, their activities of daily living, their social roles and the assessment and training they have received, as well as the wheelchair itself and the environmental surroundings [26]. We have proposed an extension to our collaborative control architecture [12] to include more in–depth models of the user's capabilities and behaviours, which takes into account developmental issues [27].

V. Prescribing Powered Wheelchairs

The Department of Health and Human Services in the US lays out some process guidelines for the prescription of powered wheelchairs [28]. In particular, emphasis is placed on assessing the patients "ability to safely use a powered wheelchair" and that their "home should provide adequate access, maneuvering space, and surfaces for the operation of a powered wheelchair." However, the literature does not define exactly what these assessments should entail.

Since 1991, the assessment and provision of powered wheelchairs in the UK has been determined by the local authorities, rather than a centralised body [29]. In analysis of the wheelchair provision system in the UK, a need was identified for both the training of the rehabilitation engineer who supplies and maintains the chairs and the involvement of a therapist who would train and monitor the patient's use of such a chair [29]. Similarly in Sweden, the assessment and prescription of powered wheelchairs is predominantly carried out by occupational therapists and physiotherapists [30].

Once a chair has been prescribed, the chair is usually manually adjusted by a rehabilitation engineer or technician to suit the individual patient's needs. Setting the controller parameters (velocity and acceleration profiles etc.) is critical to maintaining safety and ensuring the wheelchair does not behave "erratically". This undesirable behaviour can occur through heightened sensitivity to the input, or conversely by not responding promptly to the user's corrective actions [31]. We investigated how a collaborative control methodology can ensure that such erratic behaviour is not exhibited, consequently resulting in little need for corrective joystick movements [14]. Such a system that is able to automatically adapt to the user, should reduce the time required to configure the wheelchair for its new owner. Additionally, if a shared control technique is to be used to help a wheelchair user, special attention must be paid to the cognitive demands of using such a system [31]. We have carried out experiments to assess user workload, by using secondary tasks whilst driving the wheelchair in a naturalistic environment (Fig. 3) [16].

VI. Advice from Clinicians

When choosing a new wheelchair, the end user is encouraged to "test drive the new model in the real world, just as one would test drive a new car on the roads" [31]. Therefore, it follows on that experiments carried out by robotics researchers should take place in naturalistic environments, wherever possible. However, such environments should be

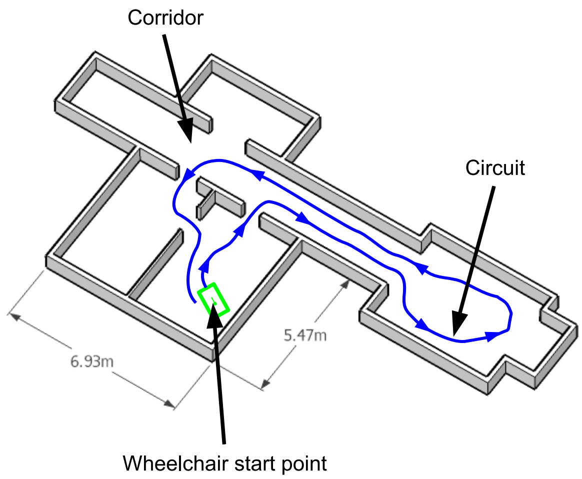

Fig. 3. We perform our evaluations in an office environment. The test course includes driving in a cluttered office space, with desks as well as along a corridor and turning in an open space. The test illustrated includes passing through 3 doorways. This map is based on data from [32]

carefully controlled to ensure that the results can be correctly compared to maintain the validity of the experiment.

The Wheelchair Skills Test, which we previously described in Section IV, was used to assess the effectiveness of a program to train occupational therapy students in driving proficiently [33]. This again highlights the importance of targeting not only the end users, but also the medical practitioners that would be prescribing the chairs to individuals and then instructing them how to use the chair effectively. When roboticists evaluate their smart chairs, they often use able–bodied subjects in the initial trials and then struggle to find mobility impaired users that would be suitable for performing a clinical trial. Perhaps trials would be more successful if medical practitioners could be used in intermediate experiments before reaching the clinical trials stage. The expertise of the medical practitioners could save a lot of time.

Practising clinicians are highly valuable when it comes to bridging the gap between engineers and patients. Therefore, we subjected our robotic wheelchair to a qualitative assessment of its performance by a qualified research physiotherapist from the Institute of Child Health at University College London. The main positive outcomes were that the interaction with the chair was natural, it responded smoothly and some specific patients could benefit from its assistance. For example, a patient who did not have sufficient control of his arm and hand had persistently been denied independent access to a powered wheelchair, until a joystick had been significantly modified and the speed severely limited. Alternatively, instead of imposing a fixed speed limit, our collaborative control system could help by dynamically limiting the speed of the wheelchair, according to the requirements of the surroundings.

However, the main drawback of the current implementation concerns the process of transferring a patient to the chair, as Yanco also noted in her experiments [20]. From the practitioner's point of view, a few small modifications would make a big difference for the patients. For example, many patients would require the footplate to be folded up, allowing them to stand in front of the chair and then lower themselves into a sitting position, before returning the footplate to the usual position. The current placement of our laser scanner partially inhibits this. Alternatively, some patients prefer to transfer to the wheelchair from the side and then swivel to face the forward direction. To facilitate this method, the right arm of the chair should be able to be temporarily folded out of the way, which would require some re–routing of the wiring between the wheelchair–computer interface and the joystick.

VII. CONCLUSIONS

The literature regarding smart wheelchairs presents seemingly conflicting views, some calling for the user to be given maximum possible control, with minimal intervention by the "smart" controller [11], others calling for autonomous solutions that require minimal input from the user [34]. This reiterates the fact that each user is different and has their own specific needs, capabilities and desires. The latter study discusses *severely* disabled patients and calls for solutions that offer automatic steering to patients who are unable to satisfactorily operate a powered wheelchair using standard interfaces (such as joysticks, sip and puff, chin control etc.) [34]. Additionally, it recommends that some patients who also suffer from cognitive impairments may benefit from a fully autonomous navigation system that has pre–programmed destinations. It seems reasonable that users should want to maximise the degree of control they leverage over their wheelchairs, but it gets to a point where, for some users, this level of control might be so imprecise that they would require an almost autonomous system.

A vast number of different methods for assessing a patients mobility status exist in the medical world. However they all follow some common themes, e.g. can the patient successfully manoeuvre through a doorway or into a lift and how promptly can they respond to changes in the environment, perhaps requiring an emergency stop. Roboticists have also performed similar evaluations on smart wheelchairs. However, in the medical world, there are examples of some standardised obstacle courses that are used to quantify the precision of a patients driving skills, whereas each research lab tends to invent its own obstacle course. Additionally, in the medical world, some assessments are carried out in the patient's own home, whereas in academia, the closest most studies get to this level of evaluation is to try and emulate a home or workplace within a controlled environment, by carefully selecting and arranging furniture.

Perhaps the key to advancing a smart wheelchair project from being of scientific interest to actually evoking positive societal improvement is to perform and evaluate experiments in a manner that is recognised by the intended profession or industry. Ideally, researchers should take the protocols from the profession and apply them throughout the research process. However, engineers often lack the expertise and experience required to single–handedly perform such trials with representative disabled end users, therefore it is recommended that alliances with medical practitioners are formed, wherever possible to facilitate this process.

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