A Cross-sectional Study Using Wireless Electrocardiogram to Investigate Physical Workload of Wheelchair Control in Real World Environments

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Abstract. The wheelchair is a key invention that provides individuals with limitations in mobility increased independence and participation in society. However, wheelchair control is a complicated motor task that increases physical and mental workload. New wheelchair interfaces, including power-assisted devices can further enable users by reducing the required effort especially in more demanding environments. The protocol engaged novice wheelchair users to push a wheelchair with and without power assist in a simple and complex environment using wireless Electrocardiogram (ECG) to approximate heart rate (HR). Results indicated that HR determined from ECG data, decreased with use of the power-assist. The use of power-assist however did reduce behavioral performance, particularly within obstacles that required more control.

Keywords: Wheelchair · Power-Assist · Heart Rate · Wireless · Real-World · Cognitive Workload · Disability

1 Introduction

The wheelchair is a tool for equality for individuals with limitations in mobility; it increases independence and opportunities to actively engage in their environment [1, 2]. Typical manual wheelchair propulsion can lead to a variety of negative health outcomes. Wheelchair users (WU) are prone to upper arm injuries related to continuous or excessive use, including damage to rotator cuff muscles – 42-66% of WU often report shoulder pain [3-5] and may suffer from bilateral carpal tunnel syndrome [6].

Reduced mobility can lead to a more sedentary lifestyle often reducing individual physical capacity for many WU [7, 8].

This is particularly problematic, as independent manual wheelchair propulsion requires adept physical capacity and cardiorespiratory fitness [9, 10]. Many musculoskeletal problems manual WU face can be prevented by reducing the use of the wheelchair (however this is wholly impractical as it would limit equality/autonomy), or altering factors related to reducing the physical load (demands of the environment) [11, 12], or increasing power (human characteristics) [13]. Electric remove the need to self-propel and therefore reduce strain injuries, while reducing metabolic demand to allow further travel and in more variable locations [14]. However they encourage an even less physically active lifestyle, predisposing users to long term health problems related to inactivity (obesity, cardiovascular disease, etc.) [15, 16].

Power Assisted Devices (PADs) are new generation mobility interfaces, that offer a middle ground solution to the problems of both manual and electric wheelchairs. They can allow users to reduce physical strain, but not at the cost of removing all the cardiovascular (CV) beneficial physical activity [13]. They are propelled in the same manner as a manual wheelchair but are fitted with small electric motors (either in the wheels or behind the wheelchair) to augment the user's physical power and allow for the social, and mobile benefits of an electric wheelchair while partially retaining the exercise component from a manual wheelchair. While PADs have intrinsic design problems, they are being increasingly considered among manual WU [17].

Wheelchair control is a complicated motor task that increases both the cognitive (or mental) and physical workload of an individual [18]. Cognitive workload (CW) refers to the limited information processing capacity of the brain demanded by a task or environment [19]. When environmental demands increase, subsequent increases in CW are generated. However if environmental demands exceed this capacity for information processing, task performance inevitably decreases [20]. Accidents or errors are a result of decreased or poor task performance [21]. Measuring CW is complex as it represents the interplay between the environmental demands (input), human characteristics (capacities), and task performance (output) on the operator [22, 23]. The association between CW and physical workload is an essential component of physical neuroergonomics, the study of the brain in relation to the control and design of physical tasks incorporating evaluations of brain and body measurements in natural environments as opposed to artificial laboratory settings and simplified tasks [24-32].

Understanding the factors in reducing/optimizing cognitive and physical workload in in order to improve task performance is important, particularly in the context of operating complex machinery such as manual wheelchairs. Excessive workload can lead to serious injuries, increased economic burden, and other maladies to and from the user [33, 34] and can further impact mobility, resulting in activity restriction, affecting social participation, health and wellbeing and quality of life [35]. Physical workload can be measured by a variety of mechanisms, however one of the more common, practical and valid measures includes heart rate (HR) [36].

In the United States alone, there are 3.6 million active WU above the age of 15, and due to our aging population, there are an additional 2 million new WU every year [37]. Therefore, it is imperative that newer generation wheelchair designs, such as PAD's, consider both physical and mental effort implications to optimize control ergonomics to improve safety and better community engagement. The objective of this study was to understand the interplay of expertise, environment, and interface during real-world wheelchair control. Therefore, this paper set out to evaluate the cognitive and physical workload as measured by behavioral task performance and HR for novice WU during manual and power-assisted wheelchair propulsion in both simple and complex environments.

2 Methods

30 novice participants (12 males) were recruited aged 31.8±9yrs. Only those physically able to propel a manual wheelchair for an extended period of time, and without cognitive disability or recent physical injury were recruited. Each participant completed a Physical Activity Readiness Questionnaire (PAR-Q) [38], and had biometric measurements of height, weight, age, skin color, hair color/type, grip strength (left and right), blood pressure, maximal speeds, seat height, and arm lengths. All participants also reported having normal or corrected-to-normal vision and were self-described to be able to control a wheelchair for up to one hour, including difficult terrain.

The study was conducted at the Oxford Brookes Sports Hall located in Oxford, UK with approval obtained from the University Research Ethics Committee with reference number UCLIC/1617/024/StaffHolloway/Herrera between 12/17 and 09/18.

2.1 Measurments and Devices

All participants used the manual wheelchair frame (QUICKIE LIFE R) weighing 10.5kg to traverse two environments detailed below. The wheelchair had a seat width of 45cm and fitted with the M24 Alber Twion (*Alber GmbH, Albstadt, Germany*) power assist wheels (additional 6kg each). The power assist was set in the ECO mode to allow for a maximal propulsion speed of 10km/hr. Participants wore a portable ECG sensor known as the EcgMove 3 (*Movisens GmbH, Karlsruhe, Germany)* across the chess below T4. Experiments were video recorded using a GoPro Hero Action Digital.

The behavioral performance during the experiment was manually recorded by two research assistants (reduced inter-rater variability) and retrospectively corrected when reviewing the video of each experiment. Total number of errors per obstacle was recorded and converted into percentages based on the maximum error count recorded by all participants. Obstacle percentage scores were averaged to give a total performance percentage (each obstacle given the equal weight/importance), where higher scores indicated better performance/fewer errors.

2.2 Environmental Design

Two environments (simple and complex) were created. The simple environment (flat terrain and free of obstacles) formed the outer rectangle of 13m x 14m for a total propulsion distance of 54m, and the complex environment (four separate obstacles) nested within a 36m inner square. Each obstacle was approximately 7m, with 1m of free space between the start and end of the obstacle to allow for clearance and preparation for the next obstacle. All obstacles were designed to mimic common conditions WU encounter, two required more power (rough terrain and incline slope), and two of which required more motor planning (cones and side slopes). The overall design of the environments and order of the obstacles are depicted in Figure 1, and further described below. The environments were set in the Oxford Brookes Sports Hall and guiding lines were provided for participants to follow.

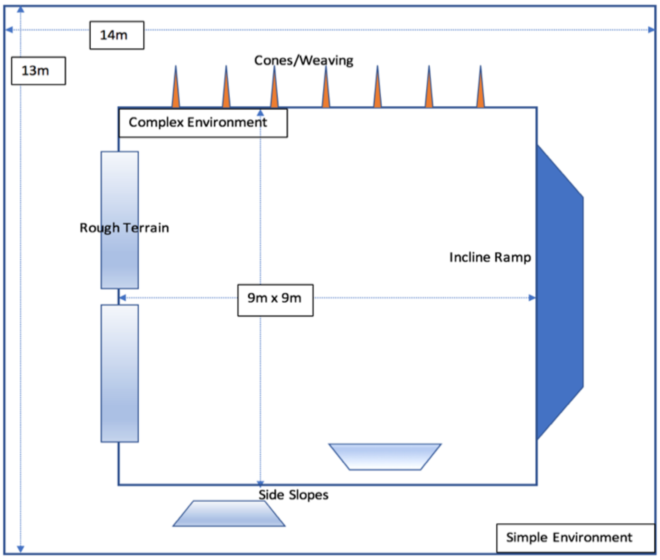

Figure 1. Sketch of outer simple and nested inner complex (with 4 obstacles) environments.

The obstacle labelled as "Rough Terrain" in Figure 1 mimicked a high friction environment requiring more power from the user, and was created using foam noodles, a common material used in obstacle designs for children with disabilities [39]. As specified by the wheelchair manufacturer manual, the height of the rough terrain was roughly set at 3cm repeated every 3-5cm, under the 5cm safety limit for the caster wheels and at a total width of 80cm. Errors while traversing rough terrain including shifting off the obstacle path, hesitating or abruptly stopping while traversing.

The incline ramp also required more power, created from 1.8cm thick plywood and set 1m wide with safety barriers to prevent participants from falling off the ramp. The incline ramp was set to American Disability Association (ADA) 2010 guidelines [37] of having a maximum of a 5° gradient at a straight on approach. The ramp was 3m long, climbing to a horizontal surface at a height of 26cm and 50cm in length that continued to an additional 3m decline at the same 5° gradient to reach back to the flat path. Physical errors while traversing the incline ramp included hitting the boundary lip of the ramp as well as hesitating/stopping during the entire obstacle.

Cones/weaving required more upper limb coordination and control. Cones were set on the guiding line of the path at 92cm apart (cone edge to cone edge) to mimic ADA guidelines [37] of acceptable wheelchair accessible door width. The start and final cone were set 1.1m from the ends of the length. The participants were asked to approach the first cone from the outside, and weave back and forth until reaching the end. Errors while traversing the cones included hitting or ignoring a cone.

The side slopes also required more upper limb coordination and control. Each slope was 2.4m in length and set at a 10° gradient to a maximum of 20cm, a height tested to be safely balanced and not lead to tipping over. They were set 1.5m from the ends of the length, and 70cm away from the path at a parallel angle. The participants were instructed to approach the first side slope at an angle using one wheel on the side slope while keeping the other wheel along the flat path. The participants were requested to exit the side slope and approach the 2nd side slope with the other wheel while maintaining the remaining wheel on the flat path. Errors while traversing the side slopes included hesitations and not maintaining a level height on the slope.

2.3 Experimental Setup

All circuits were completed in clockwise and counterclockwise directions alternating every 4 circuits during the experiment. This setup was designed to prevent fatigue. All circuits were completed in a pseudorandomized predetermined order per participant to reduce a repetitive learning effect. Ultimately, participants completed 16 circuits - 4 in a simple environment (no obstacles) without power assistance, 4 in a simple environment with power assistance, 4 in a complex environment (with obstacles) without power assistance, and 4 in a complex environment with power assistance.

To standardize the experiment participants were fixed at self-paced speeds. Each participant completed their first circuit through the complex environment without power assistance, at self-selected speeds (encouraged to make the fewest errors), to control for inter-individual differences in fitness, and recorded their first circuit completion time. All remaining circuits were attempted to be completed within that specific time (±5 seconds) regardless of interface by using a research assistant who walked beside the participant at that designated pace. The ±5 seconds accounted for fatigue and learning. Participants were given rests before the start of each circuit (30-50s) to allow for a more stable physiological baseline of HR and other measures. Total times to complete each circuit were recorded.

2.4 Statistical Analysis

Statistical analysis of behavioral performance (percentages based on errors) and HR information during the experimental procedure employed the use of linear mixed modeling implemented in NCSS (*NCSS, LLC. Kaysville, Utah, USA*). Linear mixed-effects estimates were computed with restricted maximum likelihood.

3 Results

All 30 novice behavioral performance data revealed a significant effect for the type of interface (manual or power-assist) ($F_{1,209} = 38.3877$, $p < 0.001$) depicted in Figure 2. Use of the power-assist interface led to an overall decreased performance of 5.6179% for the complex environment. Post-hoc analysis with Bonferroni adjustment revealed that the power-assist interface significantly decreased performance for only 2 of the 4 obstacles (Figure 3) - 10.6667% performance reduction for navigating the cones ($F_{1,209} = 32.1538$, $p < 0.001$), and 9.1667% reduction for navigating the side slopes ($F_{1,209} = 15.3360$, $p < 0.001$), but no significant difference in the obstacles that required more power, the rough terrain or the incline ramp.

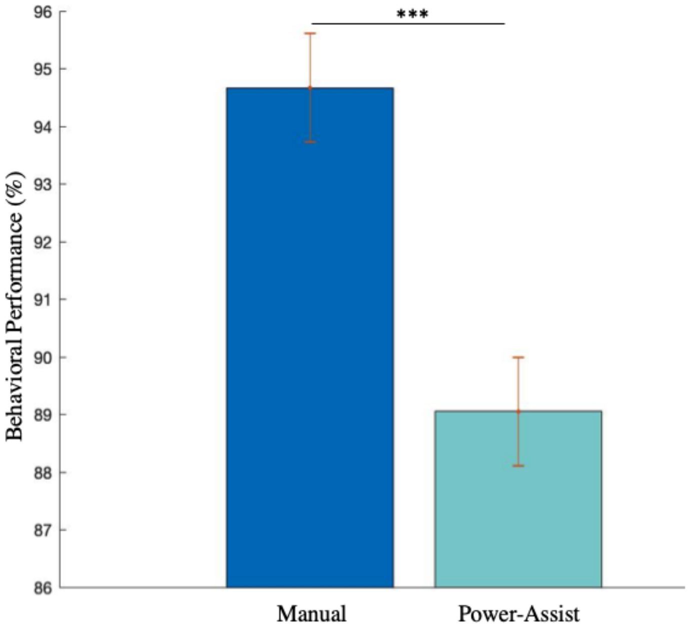

Figure 2. Overall behavioral performance comparison between the manual and power-assist interface for the entire complex environment. (***p<0.001)

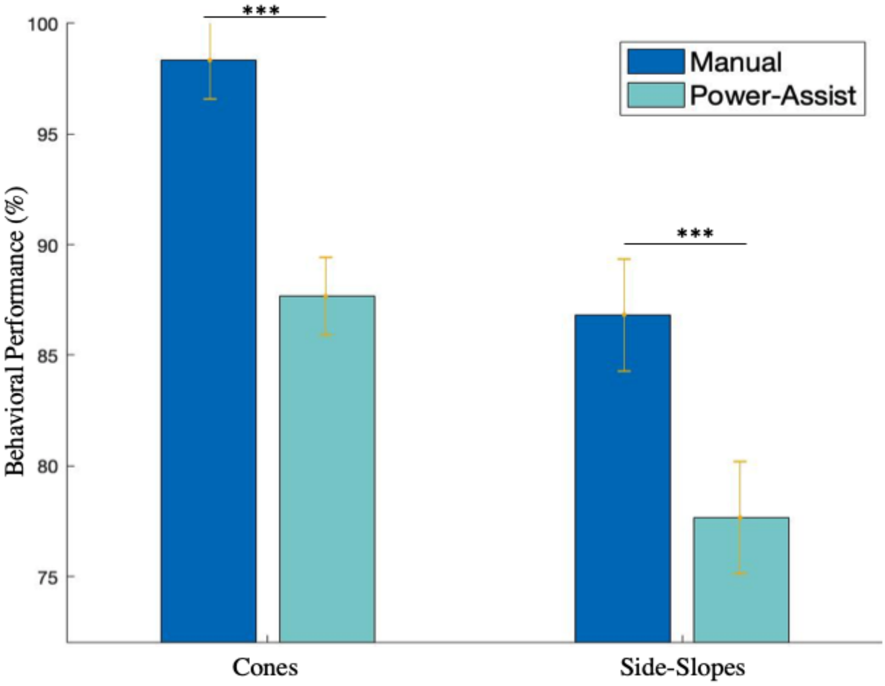

Figure 3. Behavioral performance comparison of the Cones and the Side Slopes between the manual and power-assist interface. (***p<0.001)

ECG data of 23 out of 30 novice participants was processed using a customized MATLAB script to calculate mean HR per circuit. Post-hoc analysis with Bonferroni adjustment revealed that HR of novice users decreased by 4.4767bpm with the use of power-assist ($F_{1,328} = 13.0175$, $p < 0.001$). There was no significant difference in heart rate information between the different environments and there was no significant interaction between the interfaces and the environment.

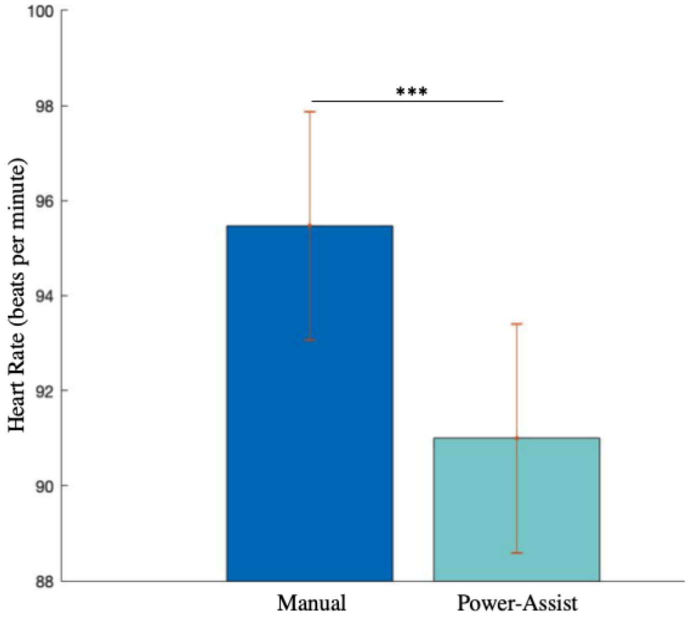

Figure 4. Heart Rate comparison of the interface. (***p<0.001)

4 Discussion

This study set out to explore the concept of PADs in physical and cognitive workload in realistic settings. As newer assistive device interfaces reach users with disabilities, it becomes paramount to begin understanding how these devices affect mental and physical workload within typical environments. We designed tasks that mimicked some of everyday situations WU would encounter. The results of this study observed that HR decreased with the use of power-assist for people learning to use wheelchairs, however at the cost of behavioral performance, particularly with particularly significant increases in errors for obstacles that require more skill and control. Therefore, this methodology along with HR measurements may aid in characterizing physical workload impact of power-assist interfaces. It appeared that new users were able to take advantage of the power assist to reduce physical workload as measured by HR while maintaining performance in tasks that require more power, but decreased performance in obstacles needing more control.

4.1 Environment

Each subject completed 8 simple, and 8 complex circuits, where the complex circuits were predicted to increase the physical workload. However, HR was not a reliable predictor for determining environmental difficulty. Furthermore, no interactions between the interface and environment were found. WU develop skills over time to negotiate inaccessible environments [40, 41], however increased environmental difficulty did not induce measurable changes in HR as expected from the literature [42]. Environmental complexity [43], as related to task demands, are directly correlated with increased CW which has been determined via evaluation of task performance [44] and cardiac responses [45], however this was not the case for measuring HR within this study.

4.2 Interface

PAD's are designed to augment the physical power of the user, to reduce metabolic effort and allow the user to expend less energy than typical manual propulsion. This design intention was indeed reflected with a statistically significant, yet small decrease in HR of 4.48bpm. Several studies have explored exercise ergonomics, and even some in wheelchair ergonomics with similar findings [46], however none to our knowledge have looked at CV responses to the newer generation wheelchair interface of power-assistance. Champagne et. al reported similar cardiorespiratory reductions with the use of mobility assistance dogs during a natural environment [47]. This reduction in physical workload may be an important factor in allowing new users to further engage in their communities for increased social participation and equality even within nonoptimal environments.

Behavioral performance did however marginally decrease with the use of the power-assistance. This may indicate that as a new interface, power assistance may lead to more accidents specifically for those new to wheelchair control. This performance reduction/increased error rate was particularly true for obstacles that required more fine control and skill (weaving through cones and balancing on the side slopes). However, PAD's may not impact quality of control in environments that require more power (like high friction/rough environments and steep incline ramps). This may lead to more informed, customized decision making on the part of the user, to determine what types of environments they may face more regularly and whether PADs are optimal for their use.

5 Conclusion

In summary, HR is a reliable measurement for assessing the potential for physical workload reduction for power-assist devices/or new mobility interfaces for new users. Power-assistance is an important factor in reducing physical workload for people learning to use wheelchairs, but perhaps at the cost of increasing minor accidents/errors. Portable non-invasive ECG is a safe and reliable measure that can be used in any simple, or physically demanding environment. Measuring HR variability may be an important factor in future studies, along with more robust measures for behavioral performance including smoothness of control. Ultimately, portable physiological measures of WU in natural environments can provide more insight for personalization of mobility devices or improved guided skill training in wheelchair control.

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