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Assisting Control for Attendant Propelled Wheelchair based on Force Velocity Relationship

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Abstract— **There is a need to develop an assisting device which can be adapted to the individual capabilities of elderly attendants, which would allow them to maintain a level of fitness when pushing a wheelchair, while minimising the risk of injury to them. Furthermore there is a need to reduce the overall energy consumption of the device in keeping with the current trends of reducing carbon emissions. The control system for attendants pushing wheelchairs that reduces the energy needed by the assisting device is an increasing trend of optimisation of assistive technology devices to individual capabilities to ensure less energy expenditure of the attendant. The control parameters for existing assisting systems for attendant wheelchair propulsion are difficult to optimise for individual capabilities. We focus on the individual propelling performance, and propose an assisting control method based on the force velocity relationship of the individual. Our proposed assisting controller generates an assisting force when the attendant's propelling force exceeds an assisting boundary defined by the force velocity relationship. In this paper, we tested the performance of the assisting controller based on force velocity (FV) relationship using simulation. The simulation used an attendant wheelchair model with parameters determined from experiments. From the simulated results of the assisting force trajectories, the FV assisting system worked as we defined. The FV assisting system used less energy consumption than the existing proportional assisting systems. Also the FV assisting system would have a limit of maximum attendant propelling power, so the distribution between the attendant force and the assisting force can be easily adjusted to the individual's force velocity relationship. Our proposed FV assisting system would be useful as it would allow an optimised system based on individual capabilities to be created for rehabilitation/training systems, which would allow optimum energy consumption when propelling a wheelchair.**

I. INTRODUCTION

The life span of elderly people increases due to advances in medical treatments. However, about 85% of people over 70 years old suffer from mobility impairments, which affect their ability to walk [1]. In addition, 25% of people who suffer from cerebrovascular diseases and osteoarthritis need to use a mobility device because of their poor mobility [2]. When elderly people go outside of their home to, for example, go shopping, meet with people or relax in a park they increase their quality of life. One device commonly used by elderly people with limited mobility is an attendant propelled wheelchair. As the average age of the population increases and the distribution of young working people to retired individuals' shifts to favour the retirees, there is an increasing deficit of young attendants. Therefore, frequently the spouses of those with mobility impairments work as attendants for loved ones in many cases; these people are often themselves elderly.

A standard attendant propelled wheelchair with occupant weighs at least 65kg. Many elderly attendants have insufficient strength to push 65kg along hard road conditions such as up a slope or over uneven road conditions. Attaching powered assisting devices to the wheelchair is one solution to reduce the propelling load [3]. The powered attendant propelled wheelchair has load cells mounted in the grips to measure the propelling force of attendants; the assisting force is generated by electric motors, which power either an auxiliary wheel or the two rear wheels directly. The assisting controller calculates the assisting force from the propelling force generated at the grips. The control rule commonly used is simply that the assisting force is proportional to the propelling force [4]. Proportional control can also be used to calculate the assisting force; in this case the assisting force is determined by the assist gain ratio. Other controllers have also been proposed such as the one that uses the reference wheelchair model to realise a mathematical light weighted wheelchair [5]. Also, the assisting control system without measuring attendant force has also been proposed [6]. These assisting methods using mathematical techniques succeed in increasing the manoeuvrability of the wheelchairs. However, they do not optimise the relationship between assisting force and individual capability in order to reduce energy expenditure of the attendant, a topic that is growing in popularity as an area where control systems can aid society. Elderly people's pushing force is very variable, which makes it difficult to adapt current control system parameters to the individual's capability. We focus on the individual propelling performance, and propose an assisting control method based on the individual's force velocity relationship. The force velocity relationship is well used to evaluate individual exercising performance, especially cycling [7, 8]. We measured steady force velocity performance of attendant propelling on a motorised treadmill [9].

Our proposed assisting controller generates the assisting force when the attendant propelling force exceeds an assisting boundary defined by a force velocity relationship. From this assisting rule, our proposed force velocity (FV) assisting system uses attendant propelling power up to the assisting boundary. The assisting boundary is easy to adjust to the individual's propelling performance. Also by using

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assisting force only when it is needed the amount of electrical energy used is reduced and, further, the attendant is able to use pushing the wheelchair as a form of moderate, controlled exercise to keep healthy. The FV assisting system also applies for training machines, rehabilitation systems and power assisting devices.

In this paper, we tested the performance of the assisting controller based on force velocity relationship using simulation. The simulation used the attendant wheelchair model with the parameters determined from experiments.

II. FORCE VELICITY ASSISTING SYSTEM AND VALIDATION

A. Assisting control based on force velocity relationship

Figure 1 shows a block diagram of the attendant and powered wheelchair system used in this study. The assisting system in the centre of Figure 1 shows the assisting system based on the force velocity relationship. The assisting system has two inputs; one is the attendant propelling force $f_h(t)$ and the other is the wheelchair velocity $v(t)$. The assisting boundary force $f_b(t)$ is determined by the wheelchair velocity $v(t)$.

$$f_b(t) = F_0 - F_R v(t) \tag{1}$$

Here, F_0 is an intercept value of the force velocity relationship and F_R is the reducing ratio, which is proportional to the wheelchair velocity. The assisting force $f_a(t)$ is calculated by equation (2).

$$f_a(t) = \begin{cases} K\big(f_h(t) - f_b(t)\big) : & f_h(t) > f_b(t) \\ 0 \quad : & f_h(t) \le f_b(t) \end{cases} \tag{2}$$

This equation means the controller generates the assisting force $f_a(t)$ when the attendant propelling force $f_h(t)$ exceeds the assisting boundary force $f_b(t)$. When the attendant force $f_h(t)$ is lower than the assisting boundary force $f_b(t)$, the assisting force is 0 because a half wave rectification element connected to the assist gain K converts negative values to zero. In Figure 2, the assisting boundary force is described as a dashed thick line. The region above the assisting boundary force generates the assisting force $f_a(t)$, however the region below the assisting boundary does not generates assisting force. When F_0=0 and F_R=0 the assisting controller works as a standard proportional controller. In this case the assisting force $f_a(t)$ is calculated by the equation (3), which is calculated for comparative purposes. It will also allow easy switching between the new FV assisting device and the proportional controller.

$$f_a(t) = K f_h(t) \tag{3}$$

The wheelchair model employs a one-dimensional simple mechanical system, see equation (4). The wheelchair model has two elements; the total mass M and rolling resistance $R(v(t))$. The rolling resistance includes bearing resistance. We assumed that the body frame of a wheelchair is rigid and inertial moments of the front casters and rear wheels can be neglected because their inertia moments are negligible compared with the mass of the wheelchair and occupant. Air drag resistance is also neglected in this wheelchair model.

$$M\frac{dv(t)}{dt} = f_d(t) - L - R(v(t)) \tag{4}$$

Here, M is the total wheelchair mass including the occupant, and $f_d(t)$ is the propelling force, which is the sum of the attendant force $f_h(t)$ and the assisting force $f_a(t)$. L is the additional load due to gravity when wheelchairs are on slopes. We assumed the rolling resistance $R(v(t))$ to be a simple linear relationship, see equation (5).

$$R(v(t)) = R_0 + Rv(t) \tag{5}$$

Here, R_0 is the static force at $v(t)$ =0. The coefficient R is the ratio of rolling resistance to wheelchair velocity and increases with wheelchair velocity. The additional load L is described in equation (6).

$$L = Mg\sin\theta \tag{6}$$

Here, L is a downward longitudinal factor of gravity due to the slope. θ is the angle of the slope.

In this study, we use the attendant model in Figure 1 to estimate assisting performance by the force velocity assisting method. The parameters in the attendant model are evaluated from experimental results shown in Figure 2. The attendant model has a desired walking velocity V_0. Human controller is commonly described as a PD controller, so we assumed that the attendant generates the propelling force by PD controller with the difference between attendant natural walking velocity V_0 and wheelchair velocity $v(t)$. Also human muscle has a delay, so we assumed the delay as a first order delay function [10]. From theses assumption, the propelling force $f_h(t)$ shows in the equation (7) below.

$$f_h(t) = \frac{P+Ds}{Ts+1}(V_0 - V(s)) \tag{7}$$

Here, P and D are the proportional and derivative coefficients respectively in the PD controller, and T is time constant in the first order system. We used T=0.3s from the previous study [10]. $V(s)$ is laplace transform of $v(t)$.

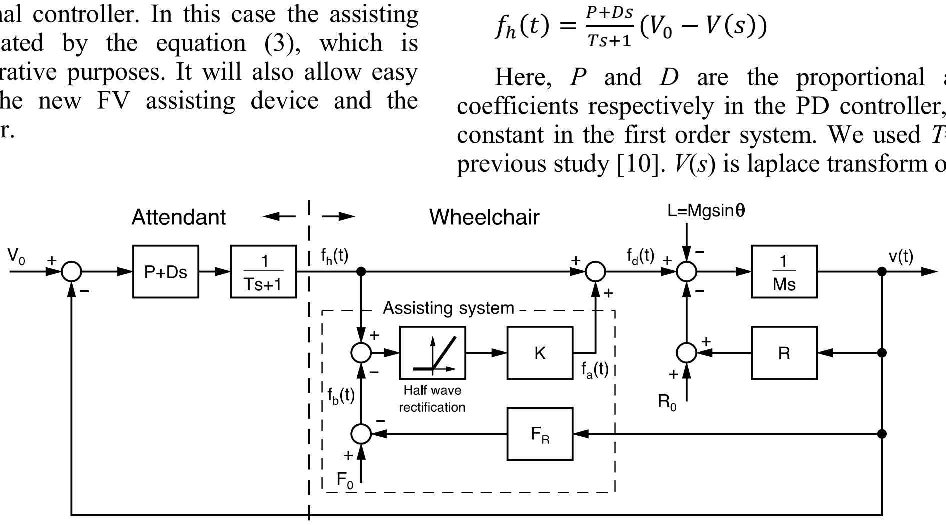

Figure 1 Block diagram of the assisting control based on force velocity (FV) relationship. The assisting system works when the attendant force f_h exceeds the assisting boundary force $f_b(t)=F_0-F_Rv(t)$. Figure 1 includes the attendant and wheelchair model to validate the FV assisting system.

B. Parameter Estimation for Attendant Wheelchair Model

The parameters of the attendant wheelchair model in Figure 1 were estimated from experiments, which were carried out with attendants pushing a wheelchair with four occupant weights and four slope conditions. We modified a commercial attendant propelled wheelchair to measure propelling force and wheelchair velocity. The wheelchair had a six-axis load cells in both grips and a rotary encoder with a pulley, which contacted and rotated with each rear wheel. The four additional weight conditions were +00, +20, +40 and +60kg. These additional weight conditions were carried out with rounded steal weights (each weight was 10kg) placed on the seat of the wheelchair. The base weight of the wheelchair including measurement devices was 36.35kg. The four slope conditions were 00, 3.6, 5.0, and 6.9deg created at the PAMELA platform at University College London. PAMELA comprises of modules of 1.2m x 1.2m, each supported by four cylinders, which enable various gradients to be created over the 58 modules. The surface of each module had nine concrete tiles (each .4m x .4m) for this study. The experiments investigated the propelling force and wheelchair velocity at voluntary constant velocities in order to estimate the FV relationship when propelling up slopes. In Figure 2, the results from one participant are shown from all experimental conditions. It this case the simple decline characteristic of the FV relationship for this participant can be estimated by $f_h(t)$=214-266$v(t)$. From the estimated FV results, we determined P =266Ns/m and V_0 = 0.8m/s. The thin dashed trajectories in Figure 2 show the experimental transient state in propelling the wheelchair. The participant increased the propelling force rapidly at low wheelchair velocity, and then decreased the propelling force along with increase of the wheelchair velocity. After about 3s, the participant continued with steady propelling at the operating point (i.e. when the propelling force is equal to the road resistance). From the transient trajectory, we estimated D = 80Ns/m. The estimated model trajectory in Figure 2 shows a good fit to the experimental results. Five participants took part in the experiments, however we show only one participant result in this paper because the tendency in all participants is similar, and deep investigation for one case is very important as a first step. Also we estimated the rolling resistance from separate experiments, where we measured the propelling force at various constant wheelchair velocities with feedback by a velocity indicator. Under constant velocity, the propelling force is equal to the rolling resistance. We used the same wheelchair to investigate the FV relationship as we did to measure the rolling resistance. In measuring rolling resistance the total weight of the wheelchair was 96.35kg, and the slope angle of the PAMELA platform was 0deg. The surface of the platform was the same for both sets of experiments. The results in Figure 2 shows the rolling resistance as a simple monotonous characteristics, so we estimated $R(v(t))$ = 11+22$v(t)$.

C. Validation Method Using Attendant Wheelchair Model

We calculated the attendant force and wheelchair velocity using the proposed FV assisting method, with parameters of F_0=71Ns/m and F_R=89 in the assisting boundary parameters from 30% inclination of $f_h(t)$=214-266$v(t)$. This is because the FV relationship for 15 min in the previous treadmill study [9] shows half the FV relationship than found in this study. From comparison with previous results, we employed a 30% FV relationship as the assisting boundary. The parameter K in the FV assisting is set as 5 because smaller K is insufficient to generate the assisting force. Also we calculated the proportional assisting cases with the parameter K = 3 for the comparison between the proportional and the FV assisting method. We investigated the trajectories of the attendant propelling force $f_h(t)$ along with the increase of the additional load force L from +00 to +100N, which is equal to the increase angle of the upward slope from 0.0 to 6.1deg. To organise the characteristic of the attendant propelling trajectories, we calculated mechanical power by multiplying the attendant force $f_h(t)$ and the wheelchair velocity $v(t)$, then classified the mechanical power to maximum power in transient state and steady power in steady state.

III. RESULTS

A. Attendant Propelling Trajectories

Figure 3 shows the attendant propelling trajectories from start to steady state in the FV and the proportional assisting method under the load condition L = +00 and 80kg. At the L=+00 kg condition with no assisting, the operating point of P_0($f_h(t)$=26.4N, $v(t)$=0.70m/s) correlates to the attendant propelling the wheelchair at a steady velocity. At this point

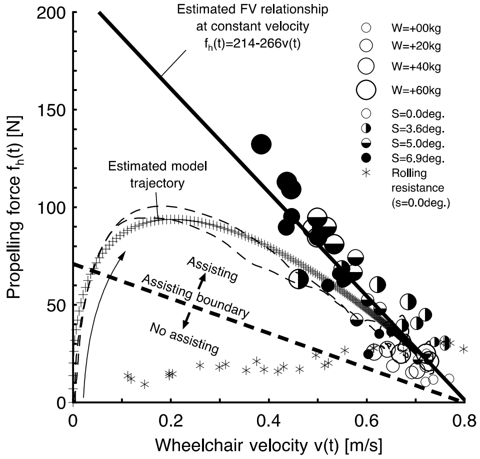

Figure 2 Experiment results to estimate the model parameters in Figure 1. The assisting system works in the region above the assisting boundary force $f_b(t)$=71-89v(t).

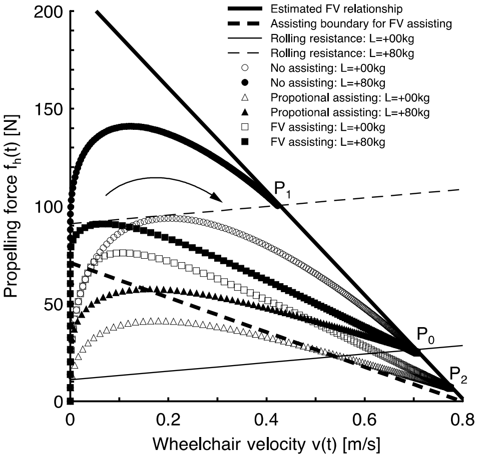

Figure 3 Simulated trajectories of the FV assisting system under the load L=+00 and 80kg. The FV assisting (F_0=71, F_R=89, and K=5) worked properly after the assisting force $f_h(t)$ exceeds the assisting bundary force $f_b(t)$.

the attendant force $f_h(t)$ was equal to the rolling resistance $R(v(t))$. In the increase of L=+80kg with no assisting, the operating point shifts from P_0 to P_1($f_h(t)$=100N, $v(t)$=0.42m/s). Therefore the attendant force $f_h(t)$ increases to deal with the additional load force L, however, the wheelchair velocity $v(t)$ decreases along with the FV relationship $f_h(t)$=214-266$v(t)$ in Figure 2.

The attendant propelling trajectory for both L=+00 and 80kg in the FV assisting reduces the attendant force $f_h(t)$ once the attendant force exceeds the assisting boundary force $f_b(t)$. Within the assisting boundary, the attendant propelling trajectories with no assisting and with the FV assisting result in the same FV relationship, however, the operating point shifted from P_0 to P_2 under the L=+00kg and from P_1 to P_0 under the L=+80kg. Therefore the assisting force $f_a(t)$ reduced the attendant force $f_h(t)$ effectively. The trajectories in the proportional assisting resulted in less attendant force $f_h(t)$ than the FV assisting case. After starting, the proportional assisting reduced the attendant force $f_h(t)$ rapidly, because the assisting force $f_a(t)$ was generated in proportional to the attendant force.

B. Normalised Maximum and Steady Attendant Power

Figure 4 shows the relationship between the additional load L, and normalised maximum and steady powers in the FV and proportional assisting. The mechanical power at vertical axis is normalised by maximum attendant power with no assisting. The normalised maximum power in the FV assisting is almost constant 0.6. However, the maximum power in the proportional assisting increases from 0.4 to 0.53 along with the increase of L. The maximum attendant power in the FV assisting is from 20.4W to 26W, larger than the maximum power 13W from the assisting boundary $f_h(t)$=71-89$v(t)$. The thin solid and dashed lines in Figure 4 show the normalised attendant power in the FV and proportional assisting respectively at steady operating point. Both normalised powers at steady state are almost same. This means that the assisting performance in steady state is the same for the FV and the proportional assisting systems. The chain line in Figure 4 shows the normalised attendant power at steady operating points. So the vertical difference between the chain line and the thin solid/dashed line is equal to the assisting power at steady state.

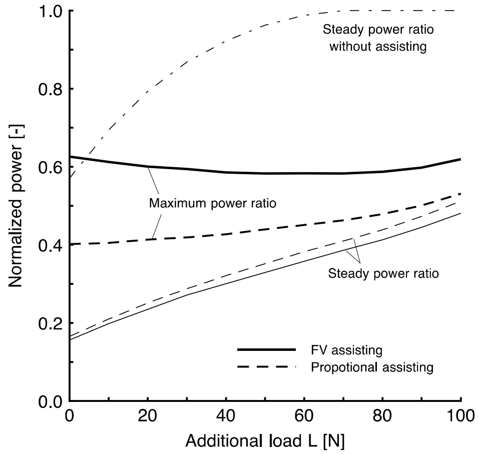

Figure 4 Normalised maximum and steady attendant power in the FV assisting system against the additional load L. The FV system used the attendant power effectively. Also the FV system generated similar the asssisting force of the proportional assisting system.

IV. DISCUSSIONS

We tested the performance of the assisting controller based on the force velocity relationship using simulation. The simulation uses the attendant wheelchair model in Figure 1 with the parameters determined from experiments in Figure 2. From the assisting force trajectories in Figure 3, the FV assisting system worked well according to the assisting rule defined in equation (2). From comparison between the FV and the proportional assisting in Figure 4, the FV assisting system use the attendant power constantly even though the load L is low. This means that the FV assisting system uses less energy consumption than the proportional assisting. Also the FV assisting system would have a limit of maximum attendant propelling power, so the distribution between the attendant force and the assisting force can be easily adjusted to the individual's force velocity relationship for elderly people. The assisting performance in steady state was almost same in the FV and the proportional assisting. This study has limitations; 1. The results were based on simulation, so we are going to validate the FV assisting system in real attendant propelled wheelchairs. 2. The selection of control parameter K is needed, because the K determines the amount of the assisting force. This means that the optimise distribution between maximum attendant power and energy consumption deeply depends on K.

Our proposed FV assisting system would be useful to optimise assisting system, rehabilitation systems and training system to individual capability.

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