Powered attendant-propelled wheelchair with assist-as-needed control based on individual physical capabilities

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Abstract

This paper discussed if a powered attendant propelled wheelchairs (PAPW) with assist-as-needed control reduces energy consumption and maximise attendant's physical activity in powered system use. This study introduced a PAPW with force velocity assist control (FVAC) based on individual capability of pushing force velocity relationship. This PAPW assists attendant pushing when more pushing force is needed over usual range of individual physical capabilities of pushing. With the PAPW, we investigated the performance of the FVAC and compared it with proportional assist control (PAC) on a flat level surface and a longitudinal slope (6.5%) with three participants. The experimental results showed that the PAPW with the FVAC reduced 50% of pushing force on the slope and this was similar performance of the PAC in terms of assisting. The FVAC also reduced 79% of mean mechanical assisting power on the flat against the PAC. These results support that the PAPW with the FVAC has flexibilities to adapt to individual physical capabilities and provides certain level of physical activities with sufficient assisting when needed, and low energy consumption for long time and distance operations for attendants.

Keywords : Assist-as-needed control, Assistive device, Attendant-propelled wheelchair, Force-velocity relationship, Iindividual physical capability

1. Introduction

Active transports by physical activities like walking and cycling brings numerous beneficial factors, especially health (Matan et al., 2015). Increased physical activities contribute healthier and longer life (Meleod et al., 2019), and it is better considerations that assistive technologies for human powered vehicles like wheelchairs, allow maximised physical activities in individual level for health and minimised energy consumption for assisting. This study focuses on powered attendant propelled wheelchairs (PAPWs) and discuss how to balance attendant's physical activities and energy consumption based on individual attendant's capability of propelling an attendant propelled wheelchair.

Attendant-propelled wheelchairs (APWs) are very useful and popular for carers to support a person with walking disability in daily activities. The APWs are designed for attendant-propulsion in which attendants push the APW with using two grips in the back of the wheelchair. The basic design of the APW is similar with self-propelled wheelchairs having two front casters and rear wheels, but doesn't have any hand rims in rear wheels, which is about a half size in common self-propelled wheelchair cases. The attendant has to provide all required physical strength to propel the APW with the occupant on various environmental terrains against resistance load (Abel and Frank, 1991b, Suzuki et al., 2009 and 2015). The weight of the APW increases propelling load as increased normal forces distributed to two casters and

two rear wheels enlarge total rolling resistance of the APW (van der Woulde 2003). The total weight of the APW with an occupant is likely to be over 100kg if the occupant is obese, for example, an adult occupant's weight in UK are 84kg (Men) and 70kg (Women) in 2010 and the APW's weight is about 10kg. On a longitudinal slope, the gravity component of the APW's weight is applied downward direction along with the slope, and the attendant has to produce pushing force against this additional load. The pushing force required for propelling the APW is physically determined by the specification of the APW and environments. Main physical parameters of the APW are total weight, dimension, the position of centre of mass, and tyre material and diameter, and main environmental factors are material, textile, and orientation of road surfaces. However, the hardness of pushing the APW depends on individual physical capability of attendants. The attendant with low physical capability of pushing might have risks in overexertion, which might result in pain to the attendant's back, shoulder and elbow joints (Lee et al., 1991). Recent ageing society faces the deficit of younger attendants, so the case in which one of aged spouse help to travel with a disabled partner, can be seen sometimes. Spousal attendants are more preferred than non-spousal attendants for older people from the view of privacy and varieties of assisting activities (Finlayson and Cho 2008). Therefore, the spouses of those with mobility impairments frequently work as attendants for loved ones in many cases; these people are often themselves elderly. Taking backgrounds mentioned above into account, the reduction of the hardness in propelling the APW is strongly demanded.

Attaching powered motor devices to the APW is one of powerful solutions to reduce the hardness in propelling the APW (Abel et al., 1991a). Powered attendant propelled wheelchair (PAPW) produces assisting force provided by electrical motors driving either an auxiliary fifth wheel or the two rear wheels. The produced assisting force is dynamically calculated by an assist controller from attendant's pushing force measured by load cell or a spring mechanism with a potentiometer in straight grips in the back of the APW. Abel developed a simple assist control system consisting of proportional gain and first order lag system. The proportional assist control (PAC) provides assisting force in proportion to the assist gain and pushing force. For example, the PAC with assist gain 1 provides the same assisting force as pushing force. A first order lag system needs to be implemented to smooth the exertion of produced assisting force. Abel adjusted the proportional gain so that typical pushing force was 15N at level and smooth ground. After Abel's work, some types of PAPWs with the PAC have been available in the market. Besides, interesting challenges to improve assist controller of PAPWs were studied in different ways. Kakimoto (1997) proposed an assist control based on an APW reference model in planar motion. Kakimoto's proposed assist control fulfilled that the PAPW was all the time performed as a light weighted APW on solid flat and level surface virtually, so attendants were able to push the PAPW without excessed hardness on various environment terrains. Kakimoto validated the proposed assist control by experiments with four participants on a treadmill and the ground with flat level surface and cross slope. Kakimoto found their proposed assist control reduced peak pushing force to 50% level in good cases. Kitagawa (2004) developed an omni-directional PAPW to assist attendant's pushing in horizontal movements. The proposed PAPW had four motorised omni-wheels and a six-axis force sensor, with an assist controller build by a proportional gain and a first order lag system mainly. To control four omni-wheels, Kitagawa used fuzzy algorithm, and the proposed PAPW was able to be driven to arbitrary direction at horizontal plane, such as sliding and circling on flat level surface, however, no evaluation of pushing force was shown. Using an observer to estimate pushing force was a technical challenge to develop an assist controller without force sensors. Ren (2007) developed a power assisted mobile vehicle based on torque observer. This vehicle was able to be driven as a human-guided powered mobile vehicle without measurement of pushing force. The assist controller was designed from the Lagragian model of the vehicle with a torque observer using the Lyapunov stability theorem. The torque observer was applied to estimate pushing force, and the vehicle was able to be driven on straight and curve on flat level surface. In these previous studies in developments of assist controllers for the PAPW were focused on technical update with mathematical techniques in the control system to improve the manoeuvrability of the PAPW.

Previous technical challenges introduced above have successfully showed positive effect in manoeuvrability to users, however, continuous assist control (AC) paradigm used in previous studies might lose attendant's exercise load and increase energy consumption because attendants are supported by PAPW in all time and have different individual physical capability. Assist-as-needed control paradigm is a method to assist user's physical work when the user needs to perform over individual usual range (Cai et al., 2006). This method was initially introduced to improve the outcome of gait rehabilitation with robotics (Cai et al., 2006 and Krishnan et al.,2013) for individual capability. For clinicians, user centred AC design is straight forward to adjust AC to individual capability, compared with machine focused AC design.
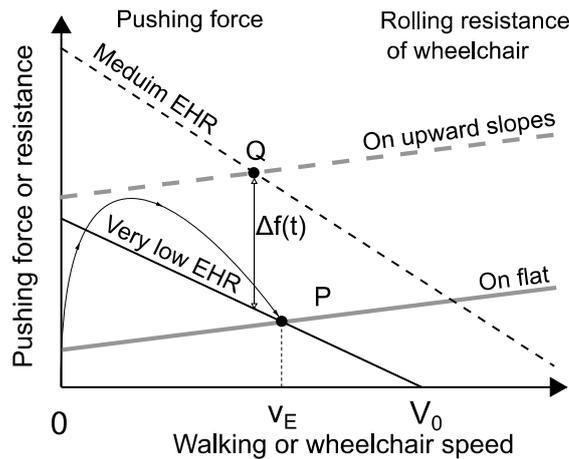
Fig. 1. Pushing force in different exercising heart rates (EHR) and resistance of a wheelchair in different road surfaces on force velocity plane. P and Q are operating points of propelling a wheelchair.

To customise exercising load and minimise energy consumption for individuals, assist-as-needed paradigm for PAPWs might bring better benefits to users compared with continuous AC paradigm.

This study proposes an assist-as-needed control paradigm based on individual physical capability for PAPWs and investigates the performance of our proposed paradigm to compare with previous continuous AC paradigm. Our novel proposed assist-as-needed control paradigm, force velocity assist control (FVAC), employed individual force velocity relationship of pushing with walking under light hardness as assist boundary, which defined attendant's maximum performance without assisting. The force velocity relationship is well used to evaluate individual exercising performance, especially cycling (Vandewalle, 1987 and Sargeant, 1994), and we investigated force velocity relationship in attendant pushing on treadmill (Suzuki et al., 2009) and on the ground (Suzuki et al., 2015). This study is aimed at investigating the performance of our proposed FVAC on flat level surface and longitudinal slopes, with three participants, to validate two points; 1) Operation of the FVAC, 2) FVAC performance on low and high load in terms of pushing and assisting forces and mechanical power, compared with the PAC.

2. Methods
2.1 Assist as needed control based on force velocity relationship

Figure 1 shows outlined pushing force by an attendant and resistance of an APW in force velocity relationship while the attendant drives the APW in straight movement. The resistance of the APW on flat surface slightly increases with the increase of wheelchair speed in dynamic state. Static resistance in nearly zero speed basically is higher than dynamic resistance and additional resistance by gravity component is applied on upward longitudinal slope. An attendant voluntarily adjusts the performance of pushing force with walking and necessary blood flow to muscles changes EHR. Both pushing force and walking speed affect individual EHR level, and pushing force monotonically decreases with the increase of walking speed at the same EHR level (Suzuki et al., 2009). Any voluntary combination of pushing force and walking speed on a line needs the same EHR level. The pushing force in walking at the low EHR level under 30% means an attendant can propel the APW long time (for example over 20 minutes) with very light subjective hardness (Suzuki et al., 2009), and at the medium EHR level both the pushing force and walking speed can be certain medium level, larger than at the low EHR level. At start when the attendant stands still and is ready to push the APW, pushing force is zero at zero wheelchair speed, and then, the pushing force increases while accelerating the APW after starting of pushing. In travelling the attendant naturally adjust pushing force and walking speed to be able to perform physical activities at low EHR level, the attendant finally continues to push the APW at steady velocity at a point P, which is a equilibrium point of pushing force by very low EHR and rolling resistance of the wheelchair on flat.

Our proposed FVAC produces assisting force when pushing force exceeds over the assisting boundary defined by

individual force velocity relationship in very low EHR. When the attendant needs to push the APW on the slope at a point Q by medium EHR, the FVAC provides assisting force based on $\Delta f(t)$. The FVAC enables to use attendant's pushing force up to the assisting boundary and provide assisting force when the attendant needs more pushing force over the endurable individual physical capability defined by the assist boundary. Figure 2(a) shows a block diagram of the FVAC in an attendant-wheelchair system. The FVAC produced assisting force $f_a(t)$ calculated by two inputs; attendant's pushing force $f_p(t)$ and wheelchair velocity $v(t)$, with Eq. (1) and Eq. (2). An assist gain K_{FV} was a key factor in calculation of the assist force $f_a(t)$ as K_{FV} directly magnified excess force $\Delta f(t)$ $(= f_p(t) - f_b(t))$ over the assist boundary force $f_b(t)$ by multiplying. Here, K_M is a total gain of mechanical driving system consisting of electric motors, driving chains, and wheels.

$$f_a(t) = K_M K_{FV}(f_p(t) - f_b(t)) \; : \; f_p(t) > f_b(t)$$
$$f_a(t) = 0 \qquad\qquad\qquad : \; f_p(t) \leq f_b(t) \qquad\qquad\qquad\qquad\qquad\qquad (1)$$

The assist boundary force $f_b(t)$ was defined by Eq. (2) with the wheelchair velocity $v(t)$ and two parameters f_M and K_D. f_M was an intercept value of the assist boundary in a force velocity relationship, and K_D was a reducing ratio in proportion to $v(t)$.

$$f_b(t) = f_b(v) = f_M - K_D v(t) \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (2)$$

f_M and K_D were experimentally determined from a force velocity relationship in very light exercise condition, in which a participant could continue exercising long time with very light hardness under EHR = 30%. Each participant's f_M and K_D, which depend on individual capability of physical strength, endurance performance, and cardiovascular system, were extracted in advance from 25% of participant's force velocity relationship, which was examined with various load conditions on the ground and on the treadmill in previous studies (Suzuki et al., 2015).

The PAC used in this study for comparison with the FVAC was defined by Eq. (3) with an assist gain K_P and the pushing force $f_p(t)$. In Figure 1(a), KFV was replaced by KP in the PAC controller and there was no feedback from wheelchair velocity v(t) and fb(t) was always zero.

$$f_a(t) = K_M K_P f_p(t) \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (3)$$

The FVAC and the PAC assist controllers with recording system were implemented in Labview with 100Hz sampling, and the assist gains used in this study were K_P =1 and 2 for the PAC and K_{FV} = 2, 3, and 4 for the FVAC. The range of 1 to 2 in assist gain K_P of the PAC was used in previous studies and K_P =1 is a simple case which assisting force is the same with pushing force. In preliminary experiments, the FVAC with K_{FV} = 2 or 3 was similar subjective feeling in pushing with the PAC with K_P =1. The first order lag system with the control gain K_{FV} or K_P was employed to smooth assisting force $f_b(t)$ and its time constant T=0.1s was chosen after preliminary tests with possible T cases.

2.2 Prototype of a PAPW

A prototype of a PAPW in Fig. 2 (b) was used for this study, after being converted from a National Health Standard APW in UK. The PAPW had two polyurethane front casters (diameter:190mm) and two polyurethane rear wheels (diameter:310mm). The wheelbase between front casters and rear wheels was 380mm. The height and width of the two grips in the back of the PAPW were 950mm and 440mm respectively, and the grips were placed in parallel with the ground surface. Six-axis load cell (AMTI model MC3A-6-250) measured pushing force produced by a participant at the stem point of each straight grip. The six-axis signals (three translational force signals F_x, F_y, F_z, and three moment signals M_x, M_y, M_z) from each load cell were measured via a strain amplifier (AMTI model MSA-6). The component F_z aligned in longitudinal direction of forward and back in straight movement, was only used for AC. The velocity of the PAPW was measured by a rotary encoder with a pulley contacted with the surface of each polyurethane rear tire. The rotational resistance by the pulley was minimised so that it did not affect to total road resistance of the PAPW. The motorised rear wheel at each side had a driving mechanism consisting of a DC electric motor (RE50: 200W, maxon motor ag) with a reduction gear head (GP52C (19:1), maxon motor ag), chain drive system, and a sprag bearing between the motor shaft and the driving sprocket. The diameters of the sprockets were 67mm (Driving) and

134mm (Driven), and the reduction ratio is 2:1. The driven sprocket was fixed to the rear wheel tightly. The torque generated by the DC motor was transferred from the motor shaft to the rear wheel by the chain system and the final reduction ratio was 38:1. The sprag bearing was used between the motor shaft and the driving sprocket to prevent from braking by slow motor rotation while travelling by the inertia of the PAPW. The DC motors in both sides were controlled by two motor drivers (ADS50/10, maxon motor ag) with shunt regulator (DSR70/30, maxon motor ag). General power supply 24V, 20A (480W) was used to drive the two DC motors to secure a stable power source. The motor drivers were used in torque control mode which can monitor produced motor torque measured by internal current in the motor. The torque constant of the DC motors was 38.5 (mNm/A). The motor torque was calculated by the multiplication with measured motor current and the toque constant and was converted to assisting force with total reduction ratio and rear wheel radius.

2.3 Procedure of experiment

The PAPW with PAC and FVAC were tested on a flat level surface (7.2 x 1.2m) and 3.6 deg. (6.5%) of a longitudinal slope (4.8 x 1.2m), which both ends connected to the same height level of flat surface. These test environments were prepared in the Pedestrian Accessibility Movement Environment Laboratory (PAMELA) at University College London. The PAMELA platform had 58 surface modules, which could reproduce various height and oriented slopes by using four or six electric actuators. The size of the surface module was 1200mm x 1200mm and its material could be replaced to many types of real kerbs and road surfaces. In this study, typical UK footway concrete pavers, which consists of 400mm x 400mm tiles, were used as the surface material. The experiments to evaluate the performance of the FVAC and the PAC were carried out with each participant on the slope first and on the flat second. The additional weight W=61kg was placed on the seat of the PAPW instead of an occupant, and the total weight of the PAPW was 108.5Kg. The orientations of the front casters were set straight towards travelling direction before each trial.
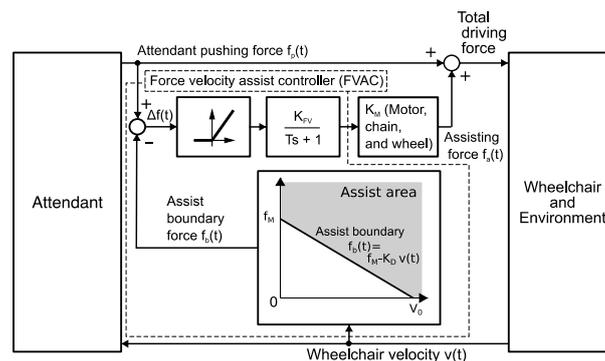
(a) Block diagram of force velocity assist control (FVAC)
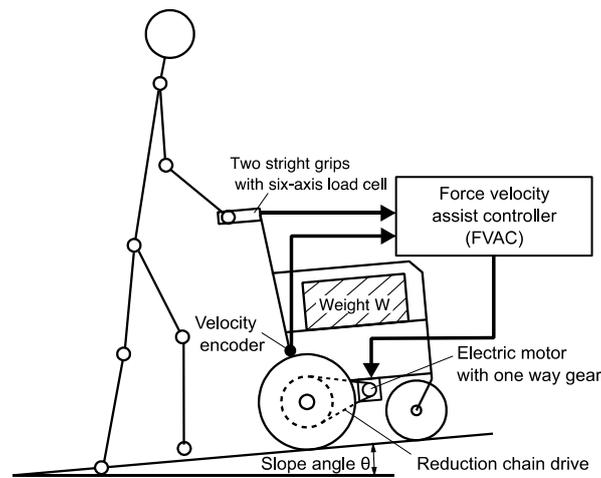
(b) Experiment setup with powered wheelchair with FVAC

Fig. 2.   Powered attendant propelled wheelchair with force velocity assist control

In trials on the slope, the rear wheels of the wheelchair were positioned at the edge between the slope and flat surface so that the whole part of the PAPW was placed on the slope. Recording was carried out during travelling from start to stop at each trial, to cover dynamic and steady situations in travelling. Before all trials, the participant was asked to propel safely naturally the PAPW at steady speed, not vigorously, while imagining as if a person was sitting on the PAPW. At the beginning of each trial, the participant had waited with slightly gripping both straight grips in the back of the PAPW, then started to push after a voice "go" sign, which was made after starting recording. All trials with different gains in the FVAC and the PAC for each participant was carried out within two hours after setting the parameters f_M and K_D of the assist boundary. Three male participants aged from 27 to 44 without any movement disorders took part in this study after agreement and informed consent. The mean height of all participants was 172cm, and mean weight was 69 kg.

To evaluate steady and dynamic performance of the FVAC and the PAC, mean and maximum pushing force, mean and maximum assisting force, mean wheelchair velocity, and maximum wheelchair acceleration were analysed. The mean data in steady condition were obtained by averaging data in steady state for two seconds after five seconds passed after starting. The maximum data in dynamic condition were analysed in a period from start to seven seconds passed. Mechanical powers of pushing and assisting were also calculated by multiplication of pushing or assisting force by wheelchair velocity, and mean and maximum mechanical powers of pushing and assisting were analysed in the same way of force cases mentioned above. To discuss the significant difference in the results, the statistical analyses with Wilcoxon rank sum test were used as the number of the data was small and it was found that the data not normally distributed in preliminary test.

3. Results
3.1 Operation of the PAPW with the FVAC

Figure 3(a) shows one typical example of time series plots how the FVAC with $K_{FV} = 3$ assisted attendant's pushing an PAPW. The plot shows pushing force $f_p(t)$, assisting force $f_a(t)$, and wheelchair velocity $v(t)$ in time series from start to steady travelling on the slope. Figure 3(b) shows trajectories of three parameters plotted on force velocity plane, which demonstrates force changes in vertical axis by velocity in horizontal axis. Without AC, a participant pushed hard in the beginning to accelerate the wheelchair and $f_p(t)$ rapidly increased and had a clear peak in a first push. While increasing $f_p(t)$, the wheelchair started to move forward, and the participant started to follow. After getting enough acceleration to travel at preferable wheelchair velocity, the participant reduced $f_p(t)$ to a certain level to keep $v(t)$ steady level, 0.37m/s in the case. $f_p(t)$ in steady travelling had a periodic component synchronised to two-leg walking, however, almost no periodic perturbation appeared in $v(t)$. With the FVAC, $f_p(t)$ dropped to 65N from 95N at the peak of the first push because the assisting force of the FVAC helped the participant to push. In steady travelling after the first push, mean level of $f_p(t)$ by the FVAC was also reduced from without assisting. The mean level of $v(t)$ with the FVAC at steady travelling was similar level without assisting. In the trajectory in Fig. 3(b), the FVAC successfully generated $f_a(t)$ after $f_p(t)$ exceeded over the assist boundary $f_b(v)$ at a point R. $f_p(t)$, $f_a(t)$, and $v(t)$ reached in steady state after transient state, and an operating point was settled on v(t) = 0.3-0.4m/s while $f_p(t)$ was slightly higher +6N from assist boundary. Basic dynamical behaviours of $f_p(t)$, $f_a(t)$, and $v(t)$ in Fig. 3 were similar under all other conditions, though the peak and steady levels in $f_p(t)$, $f_a(t)$, and $v(t)$ were changed.

3.2 Summary results with and without AC

With the tests of pushing the PAPW without and with the FVAC or the PAC from start to steady driving, all analysed parameters in mean value in steady state and maximum value are shown in Table 1. Each result in the table is a mean value of all participants' result at each experimental condition, which has three trials. Mean standard deviation for all data was less than 15% of each result. In trials, participants felt natural and easy in pushing the PAPW either with FVAC (K_{FV} =3) or with PAC (K_P=1), and both cases brought similar experience of pushing the PAPW to all participants.

Mean pushing forces are shown in Fig. 4. At flat surface, pushing forces by the FVAC were similar with the pushing force 17.2N without AC, but the pushing forces by the PAC were dropped 55% level with $K_P = 1$, and 33% with $K_P = 2$ and both cases were significantly different. At the slope, the mean pushing force 62.4N was needed without AC, and the FVAC dropped it to 55% level and the PAC dropped it to 47% level. In the table 1, maximum pushing

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(a) Time series   (b) Force velocity relationship
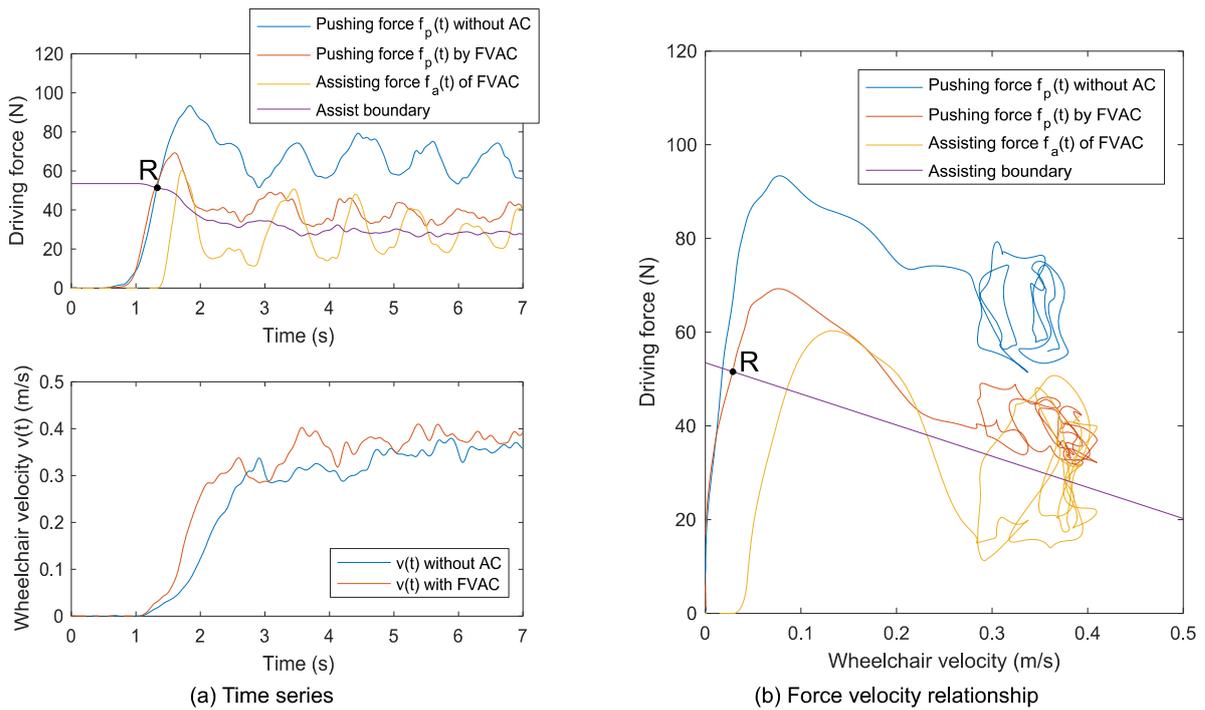
Fig. 3. Example of the operation of FVAC compared with no assist

force 58.9N at flat without AC was slightly increased to 5% level by the FVAC, however, was decreased to 64% level by the PAC. On the slope, maximum pushing force 94.4N without AC was decreased to 72% level by the FVAC, and to 60% level by the PAC. In Fig. 5, mean wheelchair velocity without AC on the flat was 0.48m/s and dropped to 0.39m/s on the slope, but this change was not significant different (p=0.09). However, the significant difference (p<0.05) in the wheelchair velocity by the FVAC and the PAC was found between on the flat and the slope. In either flat or slope condition, the wheelchair velocity was found as no significant difference between without and with AC. Participants pushed the PAPW at same level of mean velocity without AC on both flat and slope. Figure 6 shows normalised mean powers of pushing and assisting. The normalised powers P_n were calculated by Eq. (4).

$$P_n = \frac{Pushing\ power}{(Pushing\ power + Assisting\ power)} \times 100 \qquad (4)$$

Normalised power shows the rate of pushing power by total mechanical power of pushing and assisting. On both flat and slope, normalised pushing power was 1 without AC. It means that normalised assisting power was 0 in opposite. The normalised pushing powers with the FVAC (K_{FV}=3) were 88% (flat) and 55% (slope), and 47% (flat) and 47%(slope) with the PAC (K_P=1), in opposite, the normalised mean assisting powers were 12% (flat) and 45% (slope) with the FVAC (K_{FV}=3), and 53% (flat) and 53% (slope) with the PAC (K_P=1). In this case, assisting power with the FVAC dropped 79% (mean) and 11% (Maximum) on flat, and increased 14% (mean) and decreased 9% (Maximum) on slope, against the PAC. Figure 7 shows maximum wheelchair acceleration of the PAPW. Maximum acceleration without AC were 0.54m/s^2 (flat) and 0.51m/s^2 (Slope). the FVAC significantly increased the acceleration at 38% (flat) and 41% (slope) against without AC. Maximum acceleration by the PAC (K_P=1) were similar to without AC on both flat and slope, but the PAC (K_P=2) increased the acceleration at 27% (flat) and 35% (slope).

4. Discussions
4.1 FVAC operations

The aim of this study is to evaluate the performance of our proposed FVAC based on assist-as-needed control paradigm for PAPWs, compared with the PAC, which commonly uses continuous assist paradigm. First of all, the FVAC worked as designed, we found it from results in time series and a force velocity plane in Fig. 3, which shows an example of FVAC assisting with K_{FV} = 3 on the slope. The assisting force $f_a(t)$ was provided after $f_p(t)$ exceeded over

Table 1 Experimental results with attendant propelled wheelchair with FVAC and PAC

		Flat surface						Longitudinal slope: 3.6deg.(6.5%)					
		No Assist	FVAC			PAC		No Assist	FVAC			PAC	
			K_{FV} = 2	3	4	K_P = 1	2		K_{FV} = 2	3	4	K_P = 1	2
Force													
Pushing force (N)	mean	17.2	17.0	15.3	16.2	9.38	5.66	62.4	37.9	34.4	31.5	29.6	19.4
	maximum	58.9	68.0	61.8	63.2	37.9	33.5	94.1	69.5	68.1	66.0	56.4	44.6
Assisting force (N)	mean	0.00	2.11	2.21	2.46	10.5	13.3	0.00	23.7	28.1	29.8	32.8	42.9
	maximum	0.00	46.0	55.0	62.8	39.1	66.7	0.00	52.0	71.5	78.6	60.9	84.7
Wheelchair movement													
Velocity (m/s)	mean	0.48	0.48	0.50	0.47	0.48	0.49	0.39	0.38	0.40	0.41	0.41	0.43
Acceleration (m/s^2)	maximum	0.54	0.73	0.75	0.84	0.57	0.69	0.51	0.63	0.72	0.75	0.60	0.69
Mechanical power													
pushing power (W)	mean	8.17	8.02	7.44	7.53	4.45	2.73	23.6	13.9	13.3	12.3	11.7	8.01
	maximum	11.1	12.4	11.6	10.9	6.83	5.92	28.7	18.4	16.9	16.2	15.2	10.5
Assisting power (W)	mean	0.00	1.03	1.10	1.16	4.99	6.47	0.00	8.98	11.0	12.0	13.0	17.8
	maximum	0.00	11.0	12.1	14.5	7.97	15.0	0.00	18.2	22.9	26.5	17.4	24.2

$f_b(v(t))$ at the point R, and then $f_p(t)$ was effectively reduced. The participant clearly experienced the reduction of hardness in pushing. In the force velocity plane of Fig. 3(b), The assist boundary $f_b(v(t))$ decreased with the increase of wheelchair velocity $v(t)$ on force velocity plane in Fig. 3(b), and the change of $f_b(v(t))$ was shown as gradual reduction from initial value $f_b(v = 0)$ in time series plot in Fig. 3(a). In steady state, the operating point of $f_p(t)$ and $v(t)$ was slightly above from the assist boundary $f_b(v)$, so $f_a(t)$ was not zero. A reason for this difference could be that the perturbation of $f_p(t)$ caused by two-leg walking and extracted f_M and K_D of the assist boundary from the force velocity relationship in low EHR was lower than in experiments. To optimise this difference to minimum level, automatic adjustment f_M and K_D would be needed, and this feature would also be helpful to absorb daily slight difference of individual pushing performance in force velocity relationship. The wheelchair velocity in steady state by the FVAC was similar to those without AC in a case of Fig. 3 and we discuss all other cases in a section D with Fig. 5.

4.2 FVAC performance with the PAC

The evaluation of AC performances in terms of normalised mechanical power in Fig. 6, which is the total representative results of force in Fig. 4 and velocity in Fig. 5, successfully demonstrated that the FVAC worked as assist-as-needed control because the FVAC provided low assist of 12% in the flat, however, high assist of 45% on the slope. In other words, the participants provided 88% of total pushing power on the flat, and pushing power by participants reduced to 55% on the slope with the FVAC. The PAC provided 53% support by K_P=1 and 70% support by K_P=2 on both flat and slope, and it did not matter if participant felt easy or hard to push, the PAC provided always the same rate of assisting by (3) for all pushing load cases. The K_{FV} did not show strong impact on FVAC performance as the FVAC with K_{FV} = 2, 3, and 4 performed at similar level. Other factors to contribute to the FVAC performance would be f_M and K_D of the assist boundary $f_b(v)$ in Eq. (2). We used individual f_M and K_D obtained by preliminary experiments, however, there might be better adjustments to change the support ratio of the FVAC for individual cases. Main part of traveling with an APW would be on almost flat and level, so the FVAC would save up to 76% of electric energy for assisting, compared with the PAC. The FVAC has a great potential to improve energy consumption for the PAPWs with flexible customisation to individual cases.

4.3 Performance and stability by gain K_{FV} and K_P

The increase of K_{FV} in the FVAC proportionally decreased the mean pushing force in Fig. 4 and the normalised power in Fig. 6 on the slope, however, the change of K_{FV} did not affect clearly on the flat cases, in which participants pushed the PAPW near the assist boundary. This is because exceeded pushing force over the assist boundary was very low. The increase of K_P in the PAC decreased the mean pushing force and the normalised pushing power proportionally because of Eq. (3). This difference between the FVAC and the PAC clearly appeared as the sensitivity by K_{FV} and K_P.
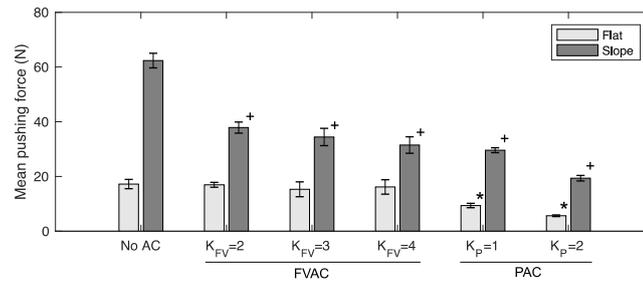
Fig. 4.   Mean pushing force: Marks *(Flat) and +(Slope) show significant difference compared with No AC.
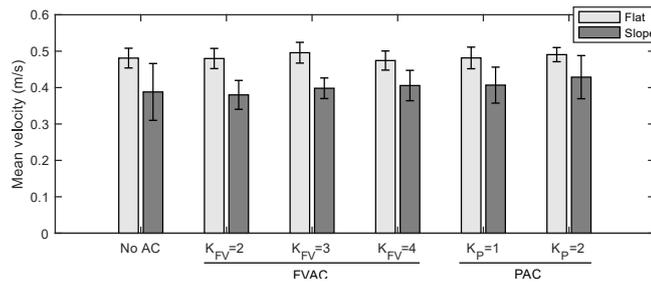
Fig. 5. Mean wheelchair velocity: All mean wheelchair velocities by the FVAC and the PAC were no significant different compared with No AC.
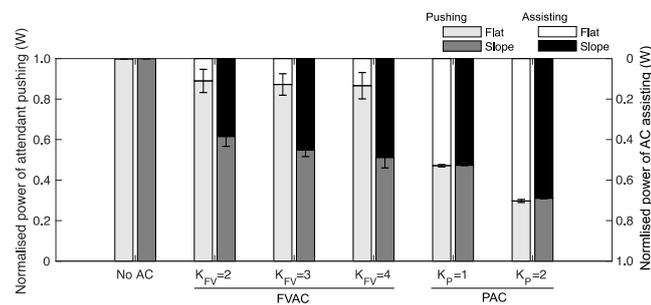
Fig. 6. Normalised power of attendant pushing and assisting
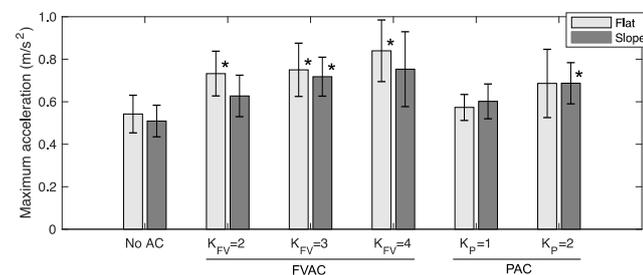
Fig. 7. Maximum wheelchair acceleration: Mark* shows significant difference compared with No AC on the flat

With the FVAC, K_{FV}=3 was the best accorded with subjective feeling of all participants after all trials. With the PAC, K_P=1 was the best and participants did not have any clear comments about the difference between the FVAC (K_{FV}=3) and the PAC (K_P=1). K_{FV}=4 of the FVAC and K_P=2 of the PAC on the flat provided participants

uncomfortable feeling that pushing was very light and the PAPW sensitively responded to pushing force, so participants needed to push carefully to avoid unneeded acceleration of the PAPW. The maximum acceleration in Fig. 7 could affect the participant's usability feeling, however, all participants were comfortable with $K_{FV}=3$ of the FVAC even though its maximum acceleration level was similar level with $K_P=2$ of the PAC. One of possible reasons for this would be the assisting force by the PAC proportionally directly magnified all small change in pushing force, however the FVAC did not provide any assisting force under the assisting boundary force. A reason why the maximum accelerations by the FVAC were higher than the PAC, would be the delay of assisting in the FVAC, as the participants might continue to push over the assist boundary with feeling of no assisting until sufficient assisting force provided by the FVAC. This time delay would cause slight less performance of the FVAC in terms of the maximum pushing force, as the participants with the PAC dynamically reduced pushing force at all time.

4.4 Difference in pushing force and wheelchair velocity by FVAC and PAC

The wheelchair velocity by the FVAC and the PAC in Fig. 5 showed that the participants pushed the PAPW at same level of mean velocity without AC on each environment condition; flat or slope. One factor to drop the wheelchair velocity was slope even though pushing the PAPW. It could be because walking on the slope needs more energy than on the level as human two legs while waking have to lift a whole body along with the slope (Minetti et al., 2002).

The easiest AC condition for participants in this study was at $K_P=2$ case of the PAC, in which participants could easily obtain more assisting force to drive faster, however, all participants in this case pushed the PAPW at similar level of mean wheelchair velocity without AC. It means that an important factor in pushing an PAPW with or without AC would be mean velocity rather than level of pushing force as participants seemed to keep preferred walking velocity while pushing the PAPW both on the flat and slope. Due to this reason, the FVAC could successfully share push load with participants, within light exercise level defined by the assist boundary, and reduced energy consumption. Participants with the PAC with the $K_P=2$ reduced pushing force to minimum level by assisting force, however, it means the PAC with $K_P=2$ consumed the highest energy in all cases of this study.

The comparison between the FVAC and the PAC in mean pushing force both on the flat and the slope clearly showed different characteristic of AC between assist-as-needed and continuous AC. On the slope, which needs high pushing force, both the FVAC and the PAC successfully reduced about a half of pushing force without AC. The FVAC had similar level of pushing force without AC on the flat, though the PAC ($K_P=1$) reduced a half of pushing force.

4.5 Limitations

In this study, the number of participants was three. One reason was that setting participant's assist boundary with the parameters f_M and K_D had needed long time experiments repeated many times (Suzuki et al., 2009). However, the results clearly showed that the FVAC performed as assist-as-needed paradigm compared with the PAC. This research team is working to find easier and quicker way to assess individual assist boundary which plays a key role in the FVAC, and automatic assessment and adjustment of individual f_M and K_D while pushing a PAPW are for future works. The other limitation is that the parameter range of the K_{FV} or the K_P in this study was not wide ranges with precise steps, however, the maximum gain of the K_{FV} and the K_P in this study were enough as the participants felt excess assisting at $K_{FV}=4$ of the FVAC and $K_P=2$ of the PAC. The optimization of the K_{FV} and time constant in the FVAC could improve its performance based on mathematical model of attendant-wheelchair system in previous studies (Uchiyama et al., 2010 and Suzuki et al., 2012), and it would be for future works as the identification of parameters in attendant behaviours still need to be investigated.

5. Conclusions

This study introduced the assist-as-needed control based on individual force velocity relationship for attendants, and investigated the performance of the PAPW with the FVAC. This study confirmed that the FVAC kept attendant free to push up to the assisting boundary and assisted attendant pushing when more pushing force over the endurable individual physical capability was needed. The validation in this study shows that the FVAC achieves similar performance to the PAC in terms of reduction of pushing force, in addition, better performance to keep certain level of attendant's physical activities and to reduce mechanical power compared with the PAC, especially 79% reduction on the flat. The flat condition would account for the main part of environments in travelling, so the driving distance and

time with the FVAC would be longer than the PAC. The FVAC also showed similar performance with the PAC on the slope condition, in which the FVAC provided sufficient assisting force to reduce pushing force to 50% level.

These results support that the PAPW with the FVAC provides certain level of physical activities, flexible customisation for individual capabilities, and low energy consumption with sufficient assisting when needed, and long time and distance operations for attendants. The FVAC has flexibilies to update its performance to individual physical capabilities. In addition, the FVAC would lower minimum power requirements of actuator and battery performance because of the FVAC's low energy consumption. With these benefits, attendants could use the PAPW with more satisfaction, and this contributes the increase of the quality of life in occupants and aged attendants together. The feature of the FVAC could be useful in development of rehabilitation and training system, which needs to impose some physical load to users with respect to users' recovery and physical strength. The FVAC could be able to apply for many human powered vehicles, for example, push rim activated powered wheelchair, powered cart system in material handling, powered bicycles and hand cycles.

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