## Evaluation of Active Passive Nature of Assistive Wearable Augmented Gait Suit for Enhanced Mobility

## Abstract

In this paper we discuss the design, control and active passive nature of the assistive wearable gait augment suit (AWGAS). AWGAS is designed to be soft, wearable, lightweight and assist walking gait by reducing muscle activation during walking. It augments walking by reducing the muscle activation of the posterior and anterior muscles of the lower limb. The suit uses pneumatic gel muscles (PGM), foot sensors for gait detection, and pneumatic valves to control the air pressure. The assistive force is provided using the motion in the loop feedforward control loop based on the foot sensors in shoes. PGMs are actuated with the help of pneumatic valves and portable air tanks. The elastic nature of the PGM allows AWGAS to assist walking in the absence of the air supply which makes AWGAS both active and passive walking assist suit. To evaluate the active and passive nature of the AWGAS, we experimented to measure surface EMG (sEMG) of the lower limb muscles. sEMG was recorded for unassisted walking, i.e., without the suit, passive assisted walking, i.e., wearing the suit with no air supply and active assisted walking, i.e. wearing the suit with air supply set at 60 kPa. The results show a reduction in the muscle activity for both passive and active assisted walking as compared to unassisted walking. The pilot trials of the AWGAS were conducted in collaboration with local farmers in the Hiroshima prefecture in Japan where feedback received is complementing the results obtained during the experiments.

## Introduction

Exoskeletons and exosuits augment human capability and reduce the chance of muscle fatigue, accidents or musculoskeletal disorders in the long term. These devices are used in settings such as factories where work involves lifting heavy objects, agriculture, walking long distances or sports. The objective of exoskeletons is to reduce human muscle efforts and augment the human ability to perform various tasks that could not be possible otherwise. Whereas, the objective of exosuits is to augment human motion and provide assistive force, thereby reducing muscle effort. With the growing elderly population, stressful work conditions, and eagerness to live a good quality of life, such devices will be critical.

Among various exoskeletons, HAL [1] makes walking easier and useful for the rehabilitation process. Wearable agri robot [2] designed to reduce physical strain on the body during farming activity. Walking assist device [3] reduces floor reaction force of the user and assist walking, stair climbing and squats motion. A passive plantarflexion assist exoskeleton [4] reduces the metabolic cost of walking. In stand-alone wearable power assist suits for caregivers, using pneumatic actuators [5], the suit provides extra strength and reduces the muscle effort required for the desired task up to 50\%. Exoskeleton to support knee joint motion [6] uses pneumatic artificial muscles to reduce the stress on the lower back and knees during the performance of loading and unloading tasks for manual workers. Wearable assistive suits for walking and lifting-up [7], with 13 DOF, and reduces muscle efforts significantly. A power assist device for standing up motion [8] for elderly or disabled to lead self-supporting lives. [9]–[12] are some of the wearable exosuits to assist walking and reduces the metabolic cost of walking using their unique methods.

These exoskeletons and exosuits are classified in various segments such as healthcare, disability support, industrial and augmented motion. They fulfill their respective purposes effectively using their unique methods, but the application outside the controlled environment is limited and not discussed especially for agriculture or outdoor environments. For augmenting human gait in an outdoor environment using exoskeleton or exosuits, wearable, portable, easy to use and light weight are some of the essential aspects to be considered, but together they are missing in the devices discussed earlier. These devices require large batteries or compressor or large air tanks for actuation of pneumatic artificial muscles (PAM), which makes device heavy and difficult to use. Most of these devices lack augmentation capability in the absence of the power sources such as batteries needed for actuator control or compressed air tanks in case of assistive suit using PAM. For the outdoor environment, it is essential that the device possess both active and passive nature to provide no disturbance or provide minimal assistance for human motion in the absence of power source. In our previous research [13], we developed a low-powered PAM, termed as pneumatic gel muscle (PGM). The PGM has an inner tube constructed with the styrene-based thermoplastic elastomer and outer protective mesh. This artificial muscle can be actuated with 50 kPa using small rubber pump and possess elastic nature to provide the minimal assistive force. Such actuation capacity is missing in the tradition PAM used for developing wearable assistive suits. In [13] K Ogawa et al. also devised a mechanism and developed an unplugged powered suit (UPS) to augment human walking.

Here, we discuss the enhanced design of the UPS using the motion in the loop feed-forward control algorithm for generating assistive force to improve the adverse effect on the antagonistic muscles discussed in [13]. In section 2 we will discuss the drawbacks of PGM and UPS, AWGAS design, biomechanics of the gait cycle, control algorithm and modeling of the assistive force generated by the PGM. In section 3, we discuss the evaluation and results of the AWGAS experiment. In section 4, we discuss preliminary trials in the rural area of the Hiroshima prefecture followed by discussion, conclusion to discuss the passive and active nature of the suit based on reduced muscle activity in the lower limb muscles.

## Background and Methodology

### Pneumatic Gel Muscle (PGM) and Unplugged Powered Suit (UPS)

In our previous research[13], we developed a low-pressure-driven pneumatic artificial muscle, PGM. Unlike McKibben PAM, the PGM is driven by low air pressure. K. Ogawa et al. reported that the PGM is elastic in nature and possesses the force-generating capacity from \SI{50}{\kilo\pascal} to \SI{300}{\kilo\pascal} of air pressure. Figure \ref{fig:pgmreal} shows the schematics and image of the actual product; it has a natural length of \SI{300}{\milli\meter}, the maximum possible contraction is \SI{200}{\milli\meter}, the maximum elongation is \SI{500}{\milli\meter}, and the maximum possible force is \SI{50}{\newton}. Based on the PGM, K. Ogawa et al. also designed and prototyped the UPS. The UPS requires no electricity but uses the walking motion to power the PGM with the help of the pump in the shoe. The evaluation of the UPS shows that it reduces the muscle efforts in the swing phase of the gait cycle; however, the effect is invisible for all the muscles of the lower limb owing to a small amount of assistive force generated. For better performance, the use of external power sources such as an air tank and a pneumatic valve control can enhance the augmentation factor of the assistive suit.

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We conducted an experiment to examine and distinguish the PGM characteristics such as generated force and actuation delay for use of rubber pumps and air tanks as source of assistive air pressure.

The experiment was conducted to examine and distinguish the PGM actuation delay for the pump and the air tank as a source of air pressure, by recording the air pressure, air flow rate, and force-generation with respect to time. The objective of this experiment was to identify the difference in the time when the air pressure is supplied to when the PGM generates the force. Figure \ref{fig:activationdelayexperiment} shows the experimental setup; it consists of a PGM with both ends hooked up, with one end attached to the Phidgets loadcell to record generated force, the air pressure sensor at the inlet valve of the PGM, and the air flow sensor to record the air flow rate at various air pressures. Table \ref{sensordetails} lists the specifications of the sensor. In this experiment, we used a rubber pump and a portable air tank to actuate the PGM. The delay was recorded for two PGM configurations, first when the PGM is attached at its rest length and second when the PGM is stretched to \SI{370}{\milli\meter}. The graphs in figure \ref{fig:pump} and figure \ref{fig:tank} show the actuation delay profiles of the PGM for the air sources of pump and air tank. We observed that when the pump is used, the delay in the generated force is approximately \SI{260}{\milli\second} and \SI{130}{\milli\second} for the rest length of \SI{300}{\milli\meter} and the stretched length of \SI{370}{\milli\meter}, respectively. However, when the air tank is used as a source, no delay is observed between the supplied air pressure and generated force.

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difference in the time when the air pressure is supplied to when the PGM generates the force. Figure 2 shows the experimental setup; it consists of a PGM with both ends hooked up with one end attached to the Phidgets loadcell to record generated force, the air pressure sensor at the inlet valve of the PGM, and the air flow sensor to record the air flow rate at various air pressures. Table 1 lists the specifications of the sensor. In this experiment, we used a rubber pump and a portable air tank to actuate the PGM. The delay was recorded for two PGM configurations, first when the PGM is attached at its rest length and second when the PGM is stretched to 370 mm. The graphs in figure 3 and figure 4 show the actuation delay profiles of the PGM for the air sources of pump and air tank. We observed that when the pump is used, the delay in the generated force is approximately 260 ms and 130 ms for the rest length of 300 mm and the stretched length of 370 mm, respectively. However, when the air tank is used as a source, no delay is observed between the supplied air pressure and generated force.

Based on this observation, we found that for the UPS, generating the assistive force/torque precisely is difficult owing to the delay and the difficulty in attaching multiple pumps in the shoe, which also disturbs normal walking. Therefore, we developed a PGM actuation control based on the gait detection system that can benefit and elevate the performance of the walking assist suit. In the next section, we discuss the design and control of a newly developed walking assist suit.

### Design of Assistive Wearable Gait Augment Suit (AWGAS)

To overcome the challenge of the UPS, we developed a new walking assist suit called the AWGAS. AWGAS is developed based on the principle of the UPS, i.e., a lightweight, wearable, low-powered assistive suit. For the AWGAS, pneumatic solenoid valves are used for the actuation control of the PGM to generate the assistive force, pneumatic regulator to control the supplied air pressure and the actuation control is designed based on the gait detection system developed using pressure sensors in the shoes. The new design enables the suit to support a walking pitch of more than two steps per second which was not possible in UPS\cite{11} and the level of augmentation can be controlled by setting the supply air pressure using regulator. K. Ogawa et al. mentioned that the maximum air pressure that the PGM can handle is 300 kPa, and PGM contraction increases with increase the supplied air pressure. Therefore, setting the maximum cutoff air pressure using air pressure regulator decides the augmentation factor of the suit during walking.

The AWGAS consists of a waist support, a knee support, PGMs attached along the quadriceps femoris, pressure sensors, pneumatic solenoid valves, controllers, and a portable air tank. Figure \ref{fig:aws} and figure \ref{fig:awgasillustration} show the overview and illustration of the applied assistive force during the swing phase of the gait cycle. Figure \ref{fig:aws} shows that the PGM is attached along the thigh muscles with the help of the waist support and knee support, while the backpack contains the controller circuit, the portable air tank, and a battery for the controller, and the pressure sensors in the shoe are connected to the controller. Figure \ref{fig:awgasillustration} illustrates the applied assistive force; the elastic nature of the PGM allows it to stretch during the stance and terminal stance phases and from the terminal stance controller that actuates the PGM for the swing phase of the gait cycle.

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The AWGAS uses the PGMs along the quadriceps femoris muscles connected across two joints: the pelvis and the knee. This configuration provides the assistive force during the swing phase of the gait cycle, and reduces the muscle effort of the quadriceps femoris during the swing phase of the gait cycle. The air pressure supply is controlled using the pneumatic solenoid valve. We also developed a gait detection system that identifies the swing phase of the individual limb. This system consists of two FSR-406 pressure sensors placed in each shoe. These are used together to detect the walking motion, standing posture, and gait cycle of the individual limb, and identify the phase of the gait cycle.

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