DEVELOPMENT OF A MOBILITY ASSIST FOR THE PARALYZED, AMPUTEE, AND SPASTIC PATIENT

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ABSTRACT

An exoskeleton system is being developed to aid in the mobilization of walking-impaired patients. New approaches to personal robotic assists have solved many classic problems with weight, power, endurance, and cost. A versatile platform of development allows for many variations and applications including mobility assist for the paralyzed, amputee, and spastic patient (MAPAS). A variety of strap on supports and braces are used, depending on the magnitude of the forces required. The MAPAS system utilizes compressed gas to power the main force producing elements, *or muscles*. Pneumatic muscles are used to provide controllable joint torque with moderate levels of pressure. These muscles are mounted to the brace, providing pull-only torque to joints. The MAPAS control system features interpreted joint mapping. The function of each leg joint is primarily directed through the output of a finger joint sensor. A six to eight sensor hand goniometer provides the system with user input. Higher control features actuated by on-board intelligent devices enable finger joint inputs to be enhanced providing balance, gait anticipation, fault-recovery, and spasm signature compensation. Ambient pressure levels of on-board reservoirs can be changed to suit changing environments ranging from heavily loaded amputee walking up stairs to the slight correction of a mild spasm. The entire system is portable with on-board batteries, compressed air reservoirs, intelligent algorithms, and goniometric sensors.

BACKGROUND

Traditionally, popular and easily available devices used to enhance personal ambulation have been limited to either simple supports or complex devices. A brace or crutch only shifts the required control, strength, or stability to the user's arms or back resulting in awkward postures and planes of force. More comprehensive mobility is accomplished through the use of wheelchairs. In both cases, having to support or maintain the assistive device itself is required and their utilization is limited to generally smooth surfaces and pathways. Functionally, both users of walkers and wheelchairs meet with a great deal of obstacles in their daily life [1].

In the VA Hospital System, over 1 million people use wheelchairs for a variety of reasons. A large population of mobility impaired people who require the use of a wheelchair or motorized scooter employ them as assistive devices as alternatives to walking braces. There are those who require a small amount of powered assistance, just enough to enhance stability or strength beyond what a walker can provide. A group of devices integrate stability enhancing mechanisms into orthosis or prosthetics to increase stability or correct for gait timing errors that wearers commonly make. These "enhancements" typically limit and restrict motion to provide a slower response, which requires more of the user's energy to perform the same action correctly [2].

The concept for powered mobility devices, mechanical limbs, bionics, and exoskeletons have existed as far back as early science fiction. The goals for such devices are both functional and aesthetic. Devices should be strong and versatile enough to provide motion which is indiscernible from unassisted gait, as well as hidden or minimally apparent for societal and psychological reasons.

Attempts at developing personal robotic systems have come up against three classic problems, weight, power, and endurance. A portable mobility enhancing system is required to not only empower the wearer, but overcome the restraints due to its own existence. Motors and batteries are very heavy and relatively inefficient, especially compared to human muscles. The relationship between batteries and power is constant. Therefore, tradeoffs between power and endurance will always need to be made. Alternative methods of powered mobility enhancement have included functional electronic stimulation (FES), a method where muscles are excited directly via external or implanted electrical impulses. Although muscle stimulators have shown some promise, it is not yet ready for mass utilization. A large gap exists for versatile powered personal mobility assistance equipment.

The growing number of patients requiring physical therapy is growing. Each year there are 1 million new cases of stroke and traumatic brain injury in the US. With the onset of spending caps on procedures and treatments, fewer therapists are doing more work, and fewer patients are being helped. Primary functions of these therapists is to maintain the range of motion (ROM), flexibility, and the proper circulation of

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these mobility impaired. In recovering stroke patients, it is critical to get them moving as soon as possible to prevent long term disabilities. Further, assisted walking is one of the preferred methods of rehabilitation in cases of injured or degenerative ambulatory related disorders. Benefits of assistive walking activity include ROM enhancement, cardiovascular exercise, physiological implications of regained freedom, and progress toward dynamic balance perception and reestablishment of synaptical pathways of sense and control functions.

Walkers provide assistance in rehabilitation by providing stability, but are very hard to use functionally in the outside world. Wheelchairs provide an alternative to walking, but offer no encouragement or promotion toward increased fitness. People who increase their use of wheelchairs over walkers reduce elements of therapy promoting increased rehabilitative promoting reambulation. A versatile portable mobility assistance system would be invaluable to the rehabilitative and physical therapy professions both as a functional assistive device for general patient use as well as a tool for enhancing therapy.

CONCEPTUAL DEVELOPMENT

The concept of a 'pneumatic muscle' has been given limited attention in control applications. Advancements and refinements in this concept lead to the development of an actuator which could be used in a portable system. The operation of a pneumatic muscle in an antagonistic arrangement is shown below in Figure 1.

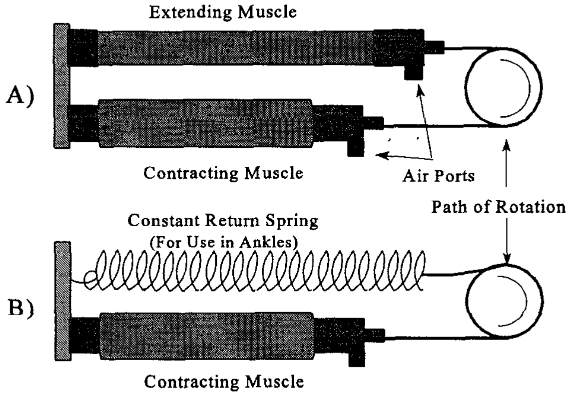

Figure 1: Simplified structure and contractile operation of pneumatic muscles. A) Opposing muscles; B) Single muscle constantly returned by spring.

A pneumatic muscle is simply an expanding balloon or tube surrounded by a woven mesh segment. When the balloon is expanded, its diameter increases stretching the diameter of the woven mesh. The increase in diameter of the mesh causes the weave angle to change, thus forcing the mesh segment length to decrease. This decrease in length produces tensile forces. Therefore, internal balloon pressure translates into a contractile force with a subsequent pulling stroke. The internal pressure determines the pulling force over the stroke length, similar to the function of a human muscle.

Powered by valve controlled compressed air, these muscles offer benefits over standard motor driven actuators. High pressure compressed gas is virtually weightless and contains considerable energy. Although, battery power is required for regulation and control, a system based on pneumatic muscles can have a very high power to weight ratio, while being compact, having fast response, and being mechanically very versatile for implementation. Various lengths and sizes were tested and optimized for utilization with an exoskeleton mounted portable system. A typical 1 inch diameter muscle with a 12 inch length could provide a 1.5 inch stroke with 130 lbs of tensile force driven by 90 PSI. These tests demonstrated the feasibility of developing a personal mobility enhancement system with this type of actuator.

MANUAL CONTROL

In most mobility disorders, the patient's impairment grows with increasingly lower spinal cord connection. Especially in spastic and muscular dystrophy patients, the injury may seem to only affect the legs from the mid thorax down, leaving full capability in the patients arms, hands, chest, and face. Spinal cord injured patients suffer from the extreme case of this, all functions below the injury level cease, whereas functions above the injury are unaffected. One solution to reambulate a person with this condition is to define a system which controls a person's lower body based on inputs from the upper body, thereby establishing translational control of one body segment from the action of another [3], shown in Figure 2. An easily adaptable mapping scheme used in the MAPAS system is that of translating finger position to in the primary inputs to gross leg position, literally letting your fingers do the walking. This finger mapping translates the user's general inputs and applies them joint per joint to the legs.

Learning to 'walk with your hands' is accomplished gradually. The first part is through a computer program prompting the prospective user to perform various ambulatory tasks. Beginning with getting up out of a chair, walking forward and turning, a user will soon learn techniques to walk around curves, climb stairs, and other complicated maneuvers. Through computer simulations and scenario testing sessions, feedback can be given and performance rated. Once satisfied in the computer realm, the user is then fitted with the legs, but is suspended by external braces to allow the wearer to safely learn the proper mapping using the real controllers.

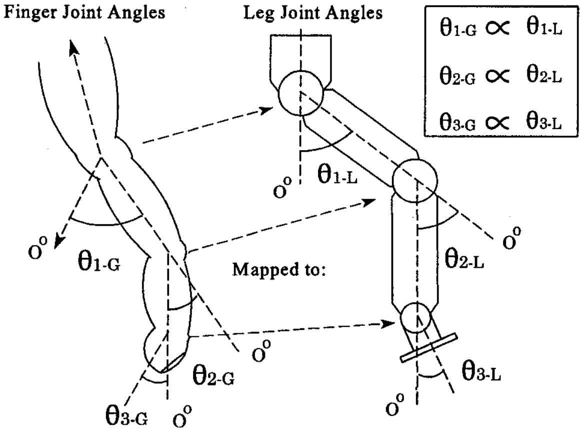

Figure 2: Anatomical mapping of finger position to desired leg position, provides basis for translational control of mobility impaired legs.

This phase introduces the user to translational control, finger mapping, sensory feedback, as well as the physical limitations of themselves and the device. The third stage is weaning off the braces and into self-controlled autonomy. This will incorporate learning balance, anticipation, timing, gate progression, and translated reaction.

Translated reaction is the ability to properly react to perform a task quickly through an alternative pathway. A wearer must learn to not use his leg controlling fingers for manual tasks like holding, pointing, and catching. Further, the hands have to be trained to provide lower body functions like recovering balance from a stumble, unexpected obstacle, or other leg-based stimulus.

Proper control of mobility functions involves much more than position mapping. Incorporation of proper balance, gait progression, timing, and higher level function is normally processed unconsciously by the brain. Although learning will occur by the user during the first few phases of introduction to the MAPAS, on-board controllers will be used to process the manual inputs to refine movements into safe and coordinated motions.

A 'bad state' watch dog algorithm will be included to correct for missing inputs required for proper gait progression and safety. Corrective measures include leg supination for directional and balance control, extension to maintain knee lock upon heel strike, counter force anticipation after toe lift, and other events requiring a large coordinated effort. In addition to the finger goniometers, the manual control brace has mode switches for function controls and additional maneuvering inputs. The thumb is used for hip rotation, which allows for turning and general maneuvering. Only the heaviest users will require hip rotation assistance as it is one of the least force intensive functions of the leg.

Another aspect of on-board control is the ability to learn the nature of the user. Spastic persons not only lose coordinated control of their legs due to complications with other disabilities, but endure gross muscle spasms. These muscle spasms are forceful random contractions requiring normal control guides or restraints to be very strong. The person with even a slight hand quiver in the control of increasingly spastic legs may face a very unstable situation. Teaching the computer to be able to be knowledgeable, such pending problems can be minimized. Algorithms can take the user's incorrect actions and 'filter them out' by the use of spasm signature detectors [4]. Therefore, the type and nature of a user's spasm may be learned and corrected for by the computer or overcome by the forces possible with the MAPAS exoskeleton.

Total MAPAS function is controlled and monitored by the manual control brace. This apparatus is a combination controller, systems monitor, and handguard. To avoid the fingers moving due to external interaction, a wrist mounted handguard is introduced. Finger joint angles are monitored by a sensored glove-like assembly. This handguard is outfitted with LCD and LED displays, switch inputs, and feedback instrumentation showing reserve air pressure, battery power, manual settings of forces, etc. The entire function can be addressed through this manual control brace. This is shown in Figure 3.

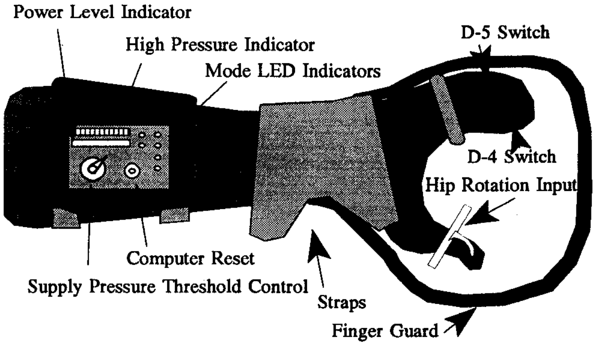

Figure 3: The MAPAS manual controller brace, allows the exoskeleton wearer to control and monitor system functions.

Incorporation of the features of this brace allow full portable operation of a variety of features required for autonomous ambulation. In cases of limited cognitive or mechanical understanding by the wearer, many of these functions can be preset, automatic, or adjustable by a co-operator.

A feature which significantly extends the versatility of the MAPAS is that of a two stage pressure platform. A single high pressure source is used to refresh the system's secondary pressure reservoirs. The ambient pressure of these secondary containers sets the maximum effort of the pulling force of each muscle. Thus, by setting the level of the refilling threshold, the net total force possible can be controlled. This allows the wearer to optimize the requirements for their own situation verses the limitations being determined by the volume of high pressure gas available. Thresholds could be increased for walking or stair climbing, and then reduced for office-chair manipulation, home activities, etc.

Once the person is sufficiently trained in translated control, they will be introduced to interacting with the specific brace which will best accommodate their needs. Since the system is open to a variety of pressures and subsequent forces, the exoskeleton structure needs to be as versatile. Therefore, the strength and ruggedness of construction of the exoskeleton brace structure can be made proportional to the amount of force required to provide the level of mobility assistance required by the wearer. Two such designs for a heavy and lighter duty mounting base are shown in Figure 4.

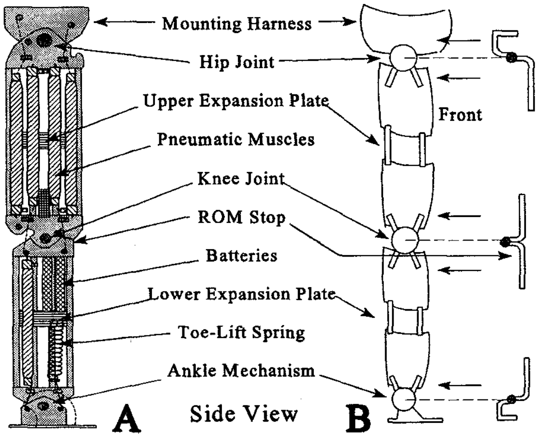

Figure 4: Two designs for MAPAS base structures, a larger force/durability system is proposed for (A), as (B) is for a lighter duty application.

Simple reinforcement of gait function and stability are lighter weight applications and may require just a strap-on plastic shell mounting system. The heavy user, those with serious mobility impairments or paralysis, may be fitted with an aluminum frame exoskeleton system to withstand the greater forces involved.

Sensor signals from the system are fed into an on-board computer. Inputs derived from the manual control brace and the finger goniometers are compared to present and expected outputs to determine the proper control of the muscle pressure valves. A complete systems diagram is shown in Figure 5. Simple versions of this system have been designed in detail and estimates of cost and weight were made. These estimates showed the MAPAS is favorable for both experimental and clinical applications.

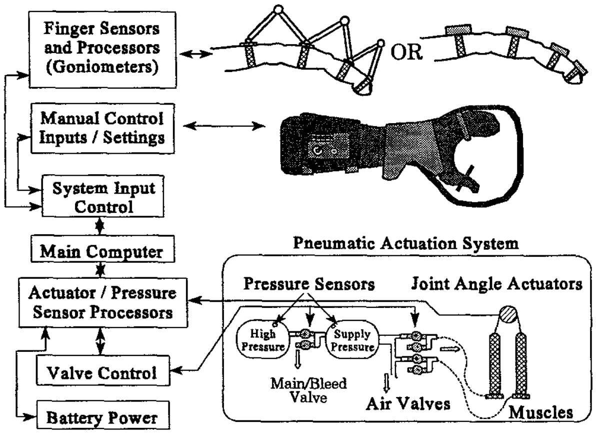

Figure 5: Systems diagram of electrical and functional pathways in the MAPAS device.

CONCLUSIONS

An investigation into compressed gas powered actuators called 'pneumatic muscles' led to the design and ongoing development of a personal assistive device for the mobility impaired. This system provides a tool for universal mobility enhancement with applications in rehabilitation, physical therapy, and real-world portable ambulatory enhancement. Features of this system address classic challenges of personal robotic systems by reducing weight, maintaining power, and offering many hours of operation. Heavier systems may enhance a normal person's ability to a state of super-mobility, allowing for tasks to be performed beyond the scope of human strength, accuracy, and speed. Development is on-going at the Armstrong Laboratory, USAF, Wright-Patterson AFB OH.

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