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FlexCVA: A Continuously Variable Actuator for Active Orthotics

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Abstract— **Active orthotic devices require actuators with high torque, a free movement mode, high efficiency, and small size and weight. The FlexCVA is a new type of actuator that addresses these requirements in a unique way. It provides continuously varying torque through the use of two belts alternately deflected by cams. The belts alternate in supplying output torque with one belt pulling the output while the slack is removed from the other belt. The drive ratio is automatically adjusted in response to the load by varying the deflection distance of the belts. The resulting actuator prototype has been demonstrated to supply up to 34 Nm of output torque, and its free movement mode allows it to be backdriven at speeds greater than 400 deg/sec.**

I. Introduction

THIS paper introduces a new type of actuator, the FlexCVA, which has been developed specifically for use in active orthotics and other applications requiring actuators with characteristics similar to human muscles. Active orthotic devices have the potential to dramatically improve the quality of life for those suffering from immobility due to disease, injury or aging, but the field is still in its infancy primarily because there has been no suitable technology that could assist human muscles in a device that is sufficiently lightweight and portable. As stated by Goldfarb in [1]:

> "Powered orthoses offer more function than purely passive hybrid systems. … However, due to the size and weight of existing DC motors and batteries, self-contained powered orthoses are not likely to be developed in the near future."

The requirements for actuators to assist large muscle groups are difficult to meet with current technology. The actuator must deliver high enough torque to offload a significant portion of the muscle force, yet be small and light enough to fit under the clothes and to be carried easily. It also must operate efficiently enough to allow the use of a small battery and it must operate with high reliability. Another key requirement is that the actuator must have a free movement mode or be easily back-drivable to avoid impeding normal movement when no assistance or resistance is desired. For instance, in an active knee orthosis, the free-movement mode is needed during the swing phase of the gait. Finally, the actuator must also allow for a wide range of speed/torque tradeoffs to allow fast, low force movement or slower high-force movement. Many of the requirements are similar to the motivation for developing continuously variable transmissions (CVTs) for transportation. A limited amount of work has been devoted to using CVTs in robotics applications [2]. However, to date there have been no CVTs with the right size, efficiency and torque characteristics for active orthotic applications.

With a suitable actuator technology, exoskeletal active orthotic devices can be developed to provide assistance for the knee, hip, ankle, shoulder or other joints [3]. The same devices can slowly transition to resistance mode to help restore muscle strength after injury or surgery. In addition, these devices show promise for robotic assistance devices to aid recovery from stroke, incomplete spinal cord injury and other neurological conditions [4].

II. Background

Previous research into active orthotics has attempted to leverage actuator technologies developed for robotics. These technologies primarily fall into three broad categories: 1) electric motors with reduction gearing, 2) pneumatic or hydraulic actuators and 3) emerging artificial muscle actuators such as those based on Electro Active Polymers (EAPs).

DC motors can be used for actuators, but the relatively high speed of the motor requires a large gear reduction to multiply the torque and drop the speed of the motor to the range required for human muscle assistance. A typical motor may run efficiently in the range of 5,000 to 20,000 RPM and require at least a 500:1 gear ratio to move a joint a few degrees per second (typically less than 10 RPM). However, a ratio that large does not allow for free movement or backdriving without the user applying considerable force. The gear reduction can be performed by a lead screw instead of other types of gearing, but this does not improve the ability to backdrive the actuator [5]. Even if the backdriving requirement could be solved by the addition of a clutch or a control system to simulate a free movement mode, a geared motor still only operates efficiently over a fairly narrow range of speeds.

Pneumatic actuators such as the McKibben muscle have had success in robotics and robotic therapy [7]-[9]. These actuators use a compressed gas to inflate a sheathed bladder that contracts lengthwise when expanded radially. However, pneumatic actuators are not applicable to mobile active orthotics due to the need for a compressor to supply the high pressure air or fluid.

Recent work in artificial muscles has centered on Electro Active Polymer (EAP) actuators [10]-[11]. These actuators

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work by applying a high voltage to flexible electrodes separated by a thin polymer layer in order to expand the polymer in the length axis while shrinking it in thickness. EAP actuators have shown promise but have drawbacks for active orthotic applications. EAP actuators are typically built with an EAP roll in tension against a spring and do not have a free movement mode. EAP actuators have not yet been scaled to the large forces required and long term reliability is a concern because they depend on working near the breakdown voltage of the materials. The ultimate size of high-force EAP actuators may also be a key constraint.

III. Theory of Operation

The FlexCVA (actuator) and FlexCVT (transmission) operate on a different principle than existing CVTs. The underlying principle of most previous CVTs is to change the ratio of one or more gears by changing the diameter of the gear, by changing the place where a belt rides on a conical pulley, or by coupling forces between rotating disks with the radius of the intersection point varying based on the desired ratio. In contrast, the FlexCVA/T operates by applying the input force to a cam or other driver to deflect a flexible belt, chain, cord or tendon ("flexor"). The flexor is anchored at one end by a one-way clutch or brake while the opposite end pulls against the load. A pair of flexors alternate between pulling the load. When one flexor is pulling the load, the slack is removed from the other flexor in preparation for the next cycle.

Figure 1 shows a diagram to illustrate the principle behind the variable force/speed of the FlexCVA/T. A flexor is anchored at one end wrapped around a pulley with a load pulling the other end. When the belt is flat, the vector of the deflection force has no component opposing the load force. In other words, an infinite load force is required to prevent the driving force from deflecting the belt to some degree. As the deflection angle increases, the same driving force can be opposed by a smaller and smaller load force. A small change in the deflection amount makes a large difference in the output force for a given deflection force. This principle is used in the FlexCVA/T to vary the mechanical advantage and provide a continuously variable transmission without gears. The movement of the load due to each flexor deflection of distance h equals $2(L_f - L_0)$.

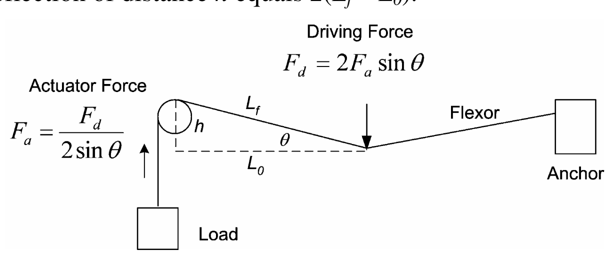

Fig. 1. When a flexible belt is anchored at one end and deflected to pull a load, the actuator output force depends on the deflection distance, h. With ideal components, as h approaches zero, $\sin\theta$ approaches zero and the actuator output force approaches infinity.

Figure 2 shows a diagram of a rotary FlexCVA. Worm gears are used as brakes to hold a sprocket stationary during the time its belt is being deflected by the cam. This technique takes advantage of the inability to backdrive a worm gear with a small lead angle. The motor driving the worm can be quite small because it rotates only when the load is on the other worm gear. The worm motor pulls the slack from the undriven belt in preparation for the next deflection. The cams are driven 180 degrees out of phase, and each cam has an increasing radius for 270 degrees of its rotation. This cam design leaves a portion of the rotation when either cam may drive the belt and provides a transition region to smoothly transfer the load from one belt to the other.

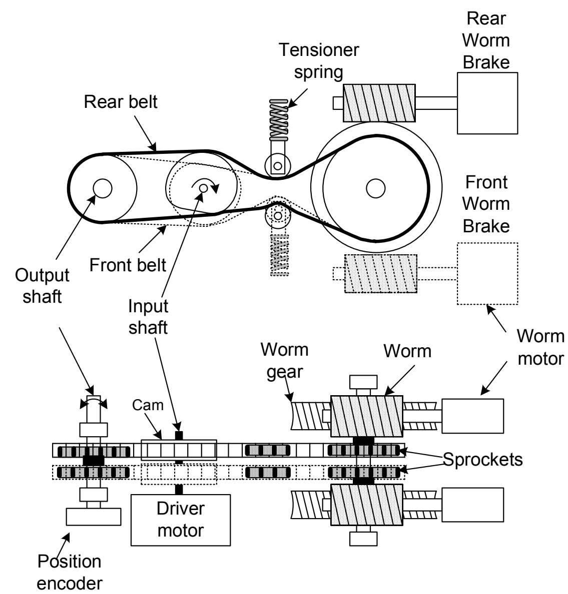

Fig. 2. Front and top diagrams of a rotary FlexCVA. The worm motors act as brakes for the front and rear sprockets. When a cam deflects one belt, the deflection force is coupled to the output shaft. After the deflection, the worm motor pulls the belt flat again while the other belt drives the output shaft.

Many variations of linear and rotary FlexCVAs are possible and are the subject of several pending patent applications. The driver does not need to be a motor-driven cam but can be any technology that can deliver a repetitive deflection force including, for instance, a piezoelectric actuator. The brakes can be implemented with friction brakes, electrostatic brakes, or any other technology that can produce a braking force. For unidirectional CVT applications, the brakes can be implemented with simple mechanical one-way clutches.

IV. Prototype Actuator

Figure 3 shows a CAD drawing of the first prototype dual-belt FlexCVA. The movement of each braking pulley is restricted by the worm gear acting as a brake or clutch. One brake is engaged while the other brake allows or forces the

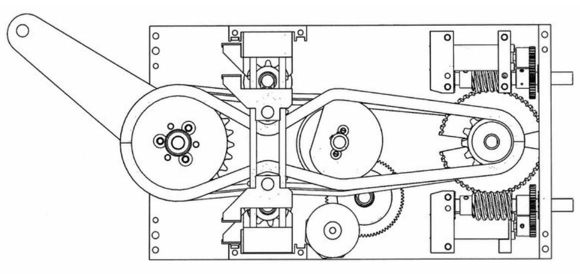

Fig. 3. CAD drawing of the prototype FlexCVA. In this version, the worm gear is split with the top half connected to the front sprocket and lower half connected to the back sprocket. Belt tensioners with linear Hall Effect sensors send belt position to the controlling electronics. Springs in the tensioners automatically reduce the drive ratio as the load increases.

second braking pulley to advance in the direction of the output movement. The belts have enough slack to allow a driver to deflect the belt between the brake and load end of the belt. The output is advanced by activating one brake while its driver deflects the top or bottom of the belt to advance the output in the desired direction. When the first driver cam is no longer deflecting the belt, the output motion continues due to the deflection of the other belt pulling against the other brake. The slack of the belt not pulling the output is removed by advancing the corresponding worm motor.

Figure 4 shows a graph of the belt movement vs. the rotation angle of the A and B cams. While any type of oscillating deflector could be used to power this type of actuator, using a cam allows the deflection vs. displacement curve to be tuned as desired. The cam is designed to nearly eliminate torque ripple and provide a smooth output free of vibration.

The transmission ratio from driver to output is controlled by the amount the belt is deflected on each cycle. The deflection is set by a spring in the belt tensioner. Small belt deflection provides high torque and low speed, while larger deflection provides lower torque and higher speed.

As the load increases, the spring in the tensioner is compressed to pull the belt away from the cam. Then the belt is deflected only for the last part of the increasing radius of the cam and the drive ratio is lowered.

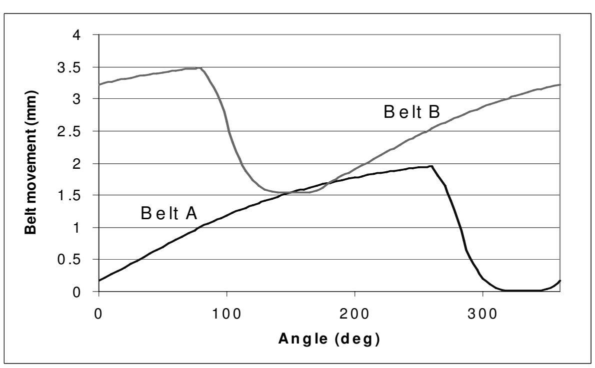

Fig. 4. Belt transfer graph showing belt movement vs. cam rotation angle. The cam shape is designed to provide nearly constant torque regardless of the cam position. As one cam nears the end of its drive phase, it decelerates to allow the other cam to take up the load.

Free movement mode is provided through the use of Hall Effect sensors to detect movement of the output sprocket by sensing changes in the tension of the top and bottom of each belt. Control systems move the worm gears to turn the sprockets to balance the tension at the top and bottom of each belt. Power dissipation in this mode is very low because the cam driver motor is stopped.

Figure 5 shows graphs of speed vs. torque for the prototype FlexCVA at several different input voltages. This graph shows measurements taken in the middle of the full performance range that extends to 34 Nm of torque and over 100 deg/s of speed. In the range of this graph, as the torque demanded by load increases, the input to output gear ratio increases from 675:1 to 3000:1. This automatic ratio adjustment gives a much wider performance range than a conventional DC motor with a fixed gear ratio.

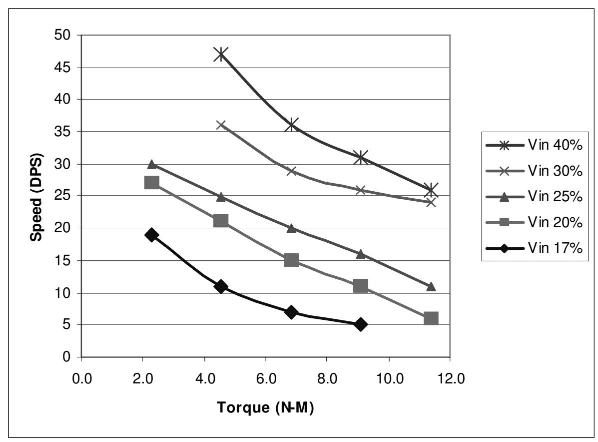

Fig. 5. Measured output speed vs. torque with the cam motor voltage set at five different values. Unlike a DC motor in which speed and voltage are related by a motor constant, the FlexCVA has three parameters (speed, torque and voltage) and allows the control system to pick any two of these as independent variables.

Figure 6 shows a photo of the current prototype. This prototype includes enhancements added as a result of initial testing of the device. The largest change from the design shown in Figure 3 is the addition of cam followers which roll against the cams and have sprockets to engage and deflect the chain. This change eliminates the friction of the chain against the cam and improves the actuator efficiency by allowing the use of quality bearings or bushings for all moving elements. Efficiency is also maintained by taking advantage of the CVT properties to run the brushless DC motor within its most efficient operating speed range. High efficiency is important to allow the use of small, lightweight batteries in portable active orthotic devices.

Another change after initial testing was to decrease the cam speed by changing the motor gear head to keep the cam speed below 1000 RPM. This change avoids resonances and suppresses vibrations and noise.

Fig. 6. Photo of the prototype FlexCVA attached to a knee brace. Future versions will reduce the size and allow the entire device to fit under loose-fitting clothing.

Table 1 gives a summary of the characteristics and results of the current FlexCVA prototype. The output torque has been tested up to its design limit of 34 Nm. The drive ratio smoothly increases as the load increases. The control system for free movement mode makes the force required to backdrive the actuator almost imperceptible. This prototype was designed primarily to demonstrate the high torque and variable ratio features and was not designed to minimize size and weight. Future versions will not require the heavy aluminum side panels and will make other improvements to reduce the size.

TABLE I
FlexCVA Prototype Test Results

Parameter	Measurement
Torque	0 to 34 Nm
Free movement speed	> 400 deg/sec
Backdrive torque	< 0.1 Nm
Power	0.3 to 70 W
Low torque in/out ratio	< 150:1
High torque in/out ratio	> 3000:1
Dimensions	208 x 120 x 50-60 mm
Weight	2.2 Kg

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V. Conclusion

The performance of the initial prototype has validated the design concepts of the FlexCVA and CVT and has shown that it is possible to produce a compact, efficient, high-torque actuator that also allows free movement. The next generation actuator design is underway, and we anticipate that it will have more than twice the torque at half of the weight and half of the thickness. This will make it viable for a portable active knee assistance device that can fit under the clothing. Future versions of the technology can be scaled further and applied to other applications in active orthotics and robotics. Plans are to continue to develop the technology and to introduce it in powered orthotic products to aid mobility and provide new forms of robotic therapy

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References

[1] M. Goldfarb, K. Korkowski, B. Harrold, and W. Durfee, "Preliminary Evaluation of a Controlled-Brake Orthosis for FES-Aided Gait," *IEEE Transactions on Neural Systems and Rehabilitation*, Vol. 11 No. 3, pp. 241-248, Sept. 2003.

[2] J. Kim, H. Yeom; F. Park, Y. Park, M. Kim, "On the energy efficiency of CVT-based mobile robots," IEEE Int'l Conf. Robotics and Automation,, vol. 2, 2000 pp.1539-1544.

[3] R. Horst, "Active Muscle Assistance Device and Method," *US Patent 6.966.882*, Issued Nov. 22, 2005.

[4] H. Krebs, N. Hogan, M Aisen, B. Volpe, "Robot-aided neurorehabilitation**."** *IEEE Trans. Rehabilitation Engineering*, V. 6, Issue 1, March 1998, pp. 75 - 87.

[5] D. Robinson, J.Pratt, D. Paluska, and G. Pratt, "Series Elastic Actuator Development for a Biomimetic Walking Robot," *IEEE-ASME Int'l Conf. on Adv. Intelligent Mechatronics*, Sept. 19, 1999.

[6] T. Takaki, T. Omata, "Load-sensitive continuously variable transmission for robot hands**,"** IEEE Int'l Conf on Robotics and Automation, Vol. 4, 2004. pp. 3391 – 3396.

[7] Chou Ching-Ping; B. Hannaford, "Measurement and modeling of McKibben pneumatic artificial muscles," *IEEE Trans. Robotics and Automation,* V. 12, Issue 1, Feb 1996, pp. 90 – 102

[8] G. Klute, J. Czerniecki,.; B Hannaford, "McKibben Artificial Muscles: Pneumatic Actuators with Biomechanical Intelligence," *Proc. IEEE/ASME Int'l Conf. Advanced Intelligent Mechatronics*, 1999, pp.221 – 226.

[9] B. Vanderborght, B. Verrelst, R. Van Ham, M. Van Damme and D. Lefeber, "A Pneumatic Biped: Experimental Walking Results and Compliance Adaptation Experiment," Proc. 5th IEEE-RAS Int'l Conference on Humanoid Robots, 2005.

[10] Y. Bar-Cohen, "Electroactive Polymers as Artificial Muscles – Reality and Challenges," Proc. the 42nd AIAA Structures, Structural Dynamics, and Materials Conf. (SDM), April 16-19 2001.

[11] R. Pelrine, R. Kornbluh, Q. Pei, S. Stanford, S. Oh, J. Eckerle, "Dielectric Elastomer Artificial Muscle Actuators: Toward Bio-mimetic Motion*,". Proc. SPIE, Smart Structures and Materials 2001: Electroactive Polymer Actuators and Devices*, ed. Y. Bar-Cohen.