Exoskeleton walking with a lightweight, low power electroadhesive clutch and spring

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Summary

Clutches can be used to enhance the functionality of springs or actuators in robotic devices. Here we describe a lightweight, low-power clutch used to control spring engagement in an ankle exoskeleton. The clutch is based on electrostatic adhesion between thin electrode sheets coated with a dielectric material. Each electrode pair weighs 1.5 g, bears up to 100 N, and changes states in less than 30 ms. We placed clutches in series with elastomer springs to allow control of spring engagement, and placed several clutched springs in parallel to discretely adjust stiffness. By engaging different numbers of springs, the system produced six different levels of stiffness. Force at peak displacement ranged from 14 to 501 N, and the device returned 95% of stored mechanical energy. Each clutched spring element weighed 26 g. We attached one clutched spring to an ankle exoskeleton and used it to engage the spring only while the foot was on the ground during 150 consecutive walking steps. Peak torque was 7.3 N-m on an average step, and the device consumed 0.6 mW of electricity. Compared to other electrically-controllable clutches, this approach results in three times higher torque density and two orders of magnitude lower power consumption per unit torque. We anticipate this technology will be incorporated into exoskeletons that tune stiffness online and into new actuator designs that utilize many lightweight, low power clutches acting in concert.

Introduction

Clutching has many uses in robotic systems, particularly in legged robotics. Clutches can disengage non-backdriveable geared motors to allow passive joint movement or engage springs to allow force development with reduced, or zero, energy cost. These approaches can lead to lower energy use in bipedal robots, lower limb exoskeletons (Collins et al, 2015), and lower-limb prostheses (Rouse et al, 2014), and suggest other devices that could assist gait. Many types of clutches, including electromagnetic, magnetorheological, and mechanical, have been used in robotic devices, but none of these have demonstrated the combination of low weight and low power consumption, and electrical controllability. Electrostatics present an alternative means of clutching (Diller et al, 2016). Electrostatic force can be developed by applying a voltage to a pair of electrodes separated by an insulating dielectric layer. Once charge is developed, power consumption is typically very low, arising only from leakage through the insulator. Very little electrode material is required, making lightweight electrodes possible. We demonstrate the electroadhesive clutch in an ankle exoskeleton, using it to engage and disengage a spring.

Methods

We created an electrostatic clutch comprised of flexible conductive electrodes coated with a high-dielectric insulator with no inherent adhesion. We placed the clutch in series with a polymer spring and performed tests of clutching force, resiliency, time to engage and disengage, and electrical power consumption. We placed several clutched springs in parallel and performed tests of stiffness selection. Finally, we incorporated the electrostatic clutch and spring into an ankle exoskeleton. During 150 consecutive steps of walking, the clutch was used to engage the spring while the foot was on the ground, and disengage it during swing.

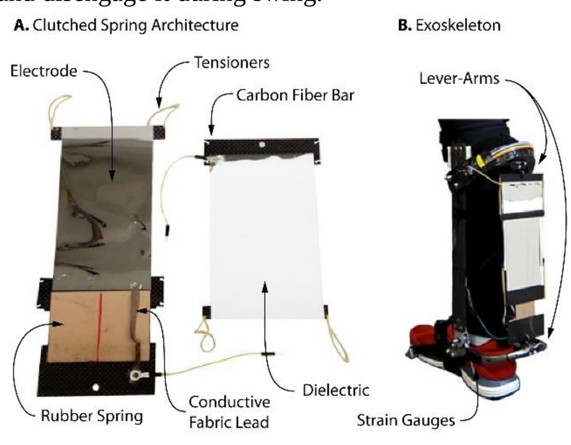

Figure 1. Clutched spring and exoskeleton.

Results

The average force reached at 100% spring strain was 100.1 ± 0.1 N (Fig. 2). The efficiency of the clutch-spring device was 94.7 ± 0.1 %. Five clutched springs placed in parallel produced a peak force of 501 N with

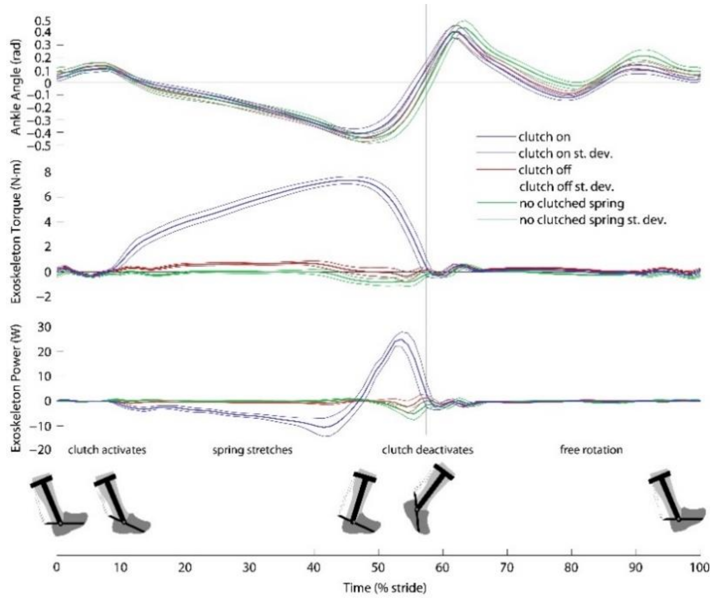

Figure 2. Average ankle angle, exoskeleton torque, and exoskeleton power during the gait cycle.

all clutches engaged and a peak force of 14 N with no clutches engaged, or a 36 times change in stiffness. Clutch release time was 29.7 ± 15.9 ms, and clutch engage time was 29.5 ± 12.0 ms. The average capacitance was 21.8 ± 5.3 nF. The maximum torque exerted by the clutched spring on the exoskeleton during walking was 7.37 ± 0.04 N-m. The linearized exoskeleton stiffness was 14.7 ± 0.9 N-m/rad. The efficiency of the exoskeleton during walking was 81.9 ± 3.6%. The maximum instantaneous power was 25.6 ± 2.4 W during push-off. The clutched spring performed 2.61 ± 0.33 J of negative work and 2.14 ± 0.29 J of positive work each step. The average electrical power consumption was 0.59 ± 0.14 mW.

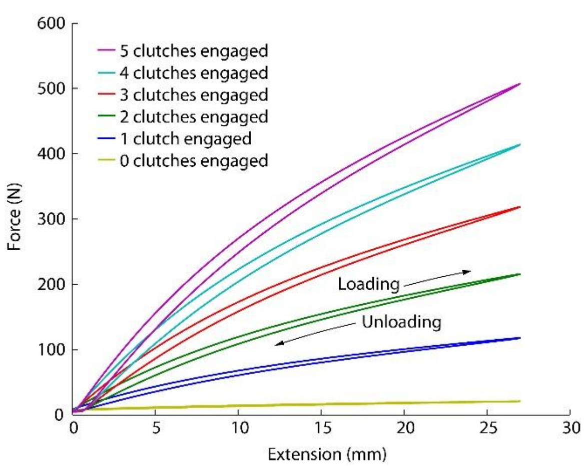

Figure 3. Force-extension for 5 clutches in parallel

Discussion

The electroadhesive clutch had a total mass of 11 g, transmitted 100 N of force, and consumed 0.6 mW of electricity during walking. This is a three-fold improvement in weight and a factor of 340 improvement in power consumption compared to the best clutches used in similar applications. Placing several clutch-spring elements in parallel allowed stiffness selection. The electroadhesive clutch-spring device controllably and reliably produced torque on the ankle exoskeleton during walking for 150 steps. Separate testing showed that the clutch fully engages and releases in less than 30 ms. This technology can be used in high-performance exoskeletons, prostheses, and walking robots, allowing the use of many separately-controlled clutches while achieving low mass and power consumption.

References

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