Energy-Efficient Actuator Design Principles for Robotic Leg Prostheses and Exoskeletons: A Review of Series Elasticity and Backdrivability

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ABSTRACT

Robotic leg prostheses and exoskeletons have traditionally been designed using highly-geared motor-transmission systems that minimally exploit the passive dynamics of human locomotion, resulting in inefficient actuators that require significant energy consumption and thus provide limited battery-powered operation or require large onboard batteries. Here we review two of the leading energy-efficient actuator design principles for legged and wearable robotic systems: series elasticity and backdrivability. As shown by inverse dynamic simulations of walking, there are periods of negative joint mechanical work that can be used to increase efficiency by recycling some of the otherwise dissipated energy using series elastic actuators and/or backdriveable actuators with energy regeneration. Series elastic actuators can improve shock tolerance during foot-ground impacts and reduce the peak power and energy consumption of the electric motor via mechanical energy storage and return. However, actuators with series elasticity tend to have lower output torque, increased mass and architecture complexity due to the added physical spring, and limited force and torque control bandwidth. High torque density motors with low-ratio transmissions, known as quasi-direct drives, can likewise achieve low output impedance and high backdrivability, allowing for safe and compliant human-robot physical interactions, in addition to energy regeneration. However, torque-dense motors tend to have higher Joule heating losses, greater motor mass and inertia, and require specialized motor drivers for real-time control. While each actuator design has advantages and drawbacks, designers should consider the energy-efficiency of robotic leg prostheses and exoskeletons beyond steady-state level-ground walking.

Keywords: Actuators, Legged Locomotion, Prosthetics, Exoskeletons, Wearable Robotics, Energy-Efficiency

1. INTRODUCTION

Robotic leg prostheses and exoskeletons can replace the propulsive function of amputated or impaired biological muscles and allow persons with mobility impairments to perform daily locomotor activities that require positive power generation via motorized hip, knee, and/or ankle joints [1-4]. These wearable robotic systems feature biomimetic design principles, whereby the actuators and mechanical structure mimic the human musculoskeletal system, the sensors and controller mimic the peripheral and central nervous systems, respectively, and the batteries mimic the metabolic power sources. Although early device designs used actuators like hydraulic systems tethered to off-board fluid pumps [5-7], the field has largely shifted towards using electromagnetic actuators for onboard power generation, specifically brushed and brushless direct current (DC) motors [1-4]. Electric motors tend to be most efficient at low torques and high speeds, with torque and power densities around 15 Nm/kg and 200 W/kg, respectively, with an efficiency of ~90% [8]. For comparison, human muscles have torque and power densities around 20 Nm/kg and 50 W/kg, respectively, with an efficiency of ~30% during concentric contractions [8].

High-speed motors are often coupled with a high-ratio transmission (e.g., ball-screw mechanism or harmonic gearing) to increase the motor torque output to that needed for legged locomotion. This design causes the robotic actuator to have high output impedance (i.e., mechanically stiff), which allows for precision position control [9]. For example, commercial powered lower-limb exoskeletons use stiff actuators to rigidly track predefined kinematic trajectories, which can benefit those with limited ability to physically

interact with and control the robotic device (e.g., persons with complete paralysis) [4]. However, these highly-geared motor-transmission systems minimally exploit the passive dynamics of human locomotion and/or other energy storage and return mechanisms [2, 9].

Traditional rigid actuators used in robotics tend to be energy inefficient, which can increase the energy consumption and thus decrease the battery-powered operating times or require larger onboard batteries [3-4]. For example, [10] reported that robotic knee prostheses under research and development weigh 2-5 kg and provide only 3 ± 2 hours of maximum battery-powered operation. Similarly, most robotic lower-limb exoskeletons provide only 1-5 hours of operating time [4]. Onboard portable power has often been considered one of the leading challenges to developing robotic exoskeletons for real-world environments [3-4]. Increased device mass and inertia could require more effort by the human musculoskeletal system during swing phase, therein reducing locomotor efficiency via higher metabolic power consumption [11]. For socket-suspended prostheses, increased mass could also cause pain and discomfort due to greater tensile forces on the human-prosthesis interface [12-13]. Highly-geared motor-transmission systems also 1) introduce nonlinearities like friction and backlash, which make torque prediction from the motor current more challenging, 2) introduce compliance, which can cause resonance issues, 3) generate higher acoustic noise from meshing gears, and 4) increase wear and the need for maintenance [14].

Motivated by these limitations and building on our previous review on regenerative braking [15], here we review two of the leading energy-efficient actuator design principles

for legged and wearable robotic systems: series elasticity and backdrivability. The goal of this review is to inform next-generation designers of robotic leg prostheses and exoskeletons of the state-of-the-art in energy-efficient systems for human-robot locomotion. Here the terms robotic and powered are used synonymously such that both systems can generate positive mechanical power. Accordingly, we did not focus on purely passive designs (e.g., the C-Leg prosthesis by Ottobock) or semi-powered systems (e.g., the Proprio Foot prosthesis by Össur). Furthermore, while some systems have used parallel elastic elements [16-18], these designs are less prevalent compared to series elasticity and thus were not the main focus of our review. We organized the paper into the following sections: 1) the mechanical energetics of legged locomotion with an emphasis on human walking, 2) the design of series elastic actuators and examples of devices that include mechanical energy storage and return, and 3) the design of backdriveable actuators with low impedance transmissions and examples of devices that include energy regeneration, including biomechanical energy harvesting.

2. ENERGY-EFFICIENT ACTUATION

Designers of robotic leg prostheses and exoskeletons are increasingly moving towards using more efficient actuators that exploit the mechanical energetics of human locomotion, including series elastic actuators and/or backdriveable actuators with energy regeneration, as subsequently reviewed. However, given that the biomechanics of walking is fundamental to the design of wearable robotic systems, the mechanical energetics of human locomotion are first discussed.

2.1 Energetics of Human Locomotion

Here joint mechanical power is defined as the product of the net joint torque and angular velocity, and joint mechanical work is the cumulative time-integral of the joint mechanical power. During energy generation, the net joint torque and angular velocity have the same sign direction and positive mechanical work is done (e.g., a concentric contraction wherein the biological muscles shorten under tension). During energy absorption, the net joint torque and angular velocity have opposite polarities and negative mechanical work is done (e.g., an eccentric contraction wherein the biological muscles lengthen under tension). This assumes that the joint torque generators are independent of adjacent joints such that biarticulating muscles spanning multiple joints are ignored. The net rate of energy generation and absorption by all muscles crossing the joint is the joint mechanical power. During walking, some mechanical energy can be recycled by conservative forces (e.g., the elastic storage and return of muscle-tendon units or the pendular dynamics of swinging limbs) and transferred between adjacent segments [19]. Most models of human locomotion ignore the elastic potential energy of deformable segments since the amount of deformation is relatively small and difficult to measure [19-21].

The energetics of human walking can be modelled by the mechanical work and power done on the total body system, as shown by Donelan and colleagues [22-24]. During single support, the stance leg resembles an inverted pendulum such that no net mechanical work is needed to move the center of mass (COM) and energy is conserved. During step-to-step transitions, however, external mechanical work by ground reaction forces is needed to redirect the body's COM velocity from one pendulum arc to another,

which is a major determinant of the metabolic cost of human locomotion [24]. To maintain steady-state level-ground walking, the leading leg performs negative mechanical work to redirect the COM velocity at foot-ground contact, while the trailing leg simultaneously performs positive mechanical work during push-off to restore the lost energy [22-23]. For example, when walking at 1.25 m/s, 15.4 ± 2.6 J of positive external mechanical work is done by the trailing leg and 12.4 ± 3.1 J of negative external mechanical work is done by the leading leg [24]. In theory, the net mechanical work during level-ground walking at constant speed should be nearly zero since there is no net change in the gravitational potential energy or translational kinetic energy of the total body system. However, compared to external mechanical work done on the center of mass, joint mechanical work can more accurately model the human musculotendon work [25] and can be used to study the distribution of energy generation and absorption throughout the lower-limbs [26-27].

Gregg and colleagues recently studied the joint mechanical power during walking using inverse dynamics [28] (Fig. 1). They developed an open-source biomechanics dataset to aid the development of biomechanical models of human locomotion and the design and control of wearable robotic systems. The dataset includes, among other variables, the hip, knee, and ankle joint mechanical power of ten (n=10) able-bodied subjects (age: 30 ± 15 years, height: 1.73 ± 0.94 m, weight: 74.6 ± 9.7 kg) walking at variable speeds and slopes. 3D-kinematics and ground reaction forces were measured using an optical motion capture system and an instrumented split-belt treadmill, respectively. The joint mechanical power (P_j) in the sagittal plane was calculated from rigid-body inverse dynamics (i.e., the dot product of the net joint torque (τ_j) and angular velocity $(\dot{\theta}_j)$) $\{P_j = \tau_j \dot{\theta}_j\}$. The joint

mechanical power (W/kg) was normalized to total body mass and percent stride (0-100%) to allow for between and within subject averaging, and interpolated heel-strike to heel-strike to have the same length. It is important to mention that muscle work, not necessarily joint work, is related to the metabolic energetics of human movement. Accordingly, the design and control of an actuation system based on only joint mechanical work and power could bring about a metabolic penalty such that the net joint work is negative but some muscles crossing the joint could be doing positive work. This knowledge of the musculoskeletal system is especially pertinent to exoskeleton systems, which operate in parallel with human muscles.

As shown in Fig. 1, the knee joint generally behaves like a damper mechanism during walking, performing net negative mechanical work with four main power phases: 1) negative mechanical power absorption at weight acceptance wherein the knee flexes under the control of an extensor moment, 2) positive mechanical power generation by the knee extensors during mid-stance such that the product of the extensor moment and angular velocity is positive, 3) negative mechanical power absorption by the extensors as the knee flexes during early swing, and 4) negative mechanical power absorption by the knee flexors during late swing to decelerate leg extension prior to heel-strike. In contrast, the ankle joint generally behaves like an actuating motor, performing net positive mechanical work with two main power phases: 1) negative mechanical power absorption at weight acceptance wherein the product of the plantarflexor moment and dorsiflexor velocity is negative, and 2) a significant positive mechanical power burst by the plantarflexors during push-off. The hip joint power is relatively small and irregular. The

joint mechanical power can be integrated over time to estimate the joint mechanical energy generated and absorbed during walking. These periods of negative joint mechanical work present an opportunity to improve actuator efficiency of robotic leg prostheses and exoskeletons by recycling some of the otherwise dissipated energy using series elastic actuators and/or backdriveable actuators with energy regeneration.

2.2 Series Elastic Actuators

Elasticity is a mechanical principle that can promote safe and efficient physical interactions, which is important for wearable robotics. One popular engineering design, pioneered by Pratt and Williamson [29], is to connect a passive elastic element (e.g., mechanical spring) in series between the actuator and external load, known as a series elastic actuator (Fig. 1). Compared to traditional rigid motor-transmission systems used in robotics, series elastic actuators have lower output impedance, greater shock tolerance and efficiency during foot-ground impacts, higher backdrivability via lower reflected inertia, and can store and return elastic energy during periods of negative and positive mechanical work, respectively [29]. Energy recycling via series compliance can improve actuator efficiency by reducing the peak power and energy consumption of the electric motor, the quantity of which is dependent on the elastic element design (i.e., the spring-mass system dynamics ideally matches the external load, thus requiring only a reactionary torque by the motor) [11, 16]. This actuator design is bioinspired such that the elastic element stores and returns mechanical energy similar to human muscle-tendon units as characterized by Hill muscle models with both active contractile and series elastic elements [21].

Since series elasticity can reduce the mechanical power and torque requirements of the electric motor, this can further improve locomotor efficiency by reducing the size and weight of the onboard motors and batteries. Energy efficiency in legged locomotion can be quantified using cost of transport $\left\{COT = \frac{E}{Mgd}\right\}$, where E is the energy consumed by a system of mass (M) to travel distance (d) [11]. For example, the Cassie bipedal robot, designed based on passive dynamics and series elastic actuation, has a cost of transport of ~0.7 such that the 30 kg robot consumes 200 W of electrical power while walking at 1 m/s [11]. In comparison, humans have a cost of transport of around 0.2. The hydraulically-actuated Big Dog quadrupedal robot has a cost of transport of ~15 [11].

Series elastic actuators have also been applied to robotic leg prostheses and exoskeletons (Fig. 2). For example, [30] published on modelling and optimal control of an energy-recycling actuator with an electroadhesive clutch and spring arranged in parallel with the electric motor. Their simulations showed that including parallel elasticity in the actuator design reduced the electrical power consumption by ~57%. In another example, Gregg and colleagues used non-parametric convex optimization to optimize the stiffness of the elastic element to minimize peak power and energy consumption for arbitrary reference trajectories while satisfying actuator constraints [31-34]. Adding their optimized spring element to a robotic ankle prosthesis reduced the peak power and energy consumption during walking from 450 W to 132 W and from 33 J to 25 J per stride, respectively [34]. Other examples of wearable robotics using series elastic actuators include [17-18, 35-40].

Herr and colleagues developed several generations of robotic knee prostheses with series elasticity [41-47]. One prototype included a continuously variable transmission between the motor and elastic element to operate the motor at optimal torque-speed regimes with highest efficiency by continuously varying the transmission ratio [44]. Another prototype included a clutchable series elastic actuator, whereby an electromagnetic clutch arranged in parallel with the series elastic actuator supplied a reactionary torque when the task dynamics were elastically conservative and mechanical energy was recycled by the spring element [41, 46]. The clutchable series elastic actuator consumed ~70% less electrical energy during walking compared to a series elastic actuator without the clutch mechanism [41]. Despite these performance benefits, actuators with series elasticity tend to have lower output torque, increased mass and architecture complexity due to the added physical spring, and limited force and torque control bandwidth [1].

2.3 Regenerative Actuators

2.3.1 Backdrivability

In recent years, torque-dense motors with low-ratio transmissions (<20:1), known as quasi-direct drives, have been used to likewise achieve low output impedance and high backdrivability and efficiency [48]. The use of low transmission ratios in legged and wearable robotic systems has been growing due to advances in torque-dense “pancake” motors [49] largely driven by the drone industry. These actuators generate high output torque by increasing the motor torque density (torque per unit mass) rather than the transmission ratio, therein circumventing the negative effects of high gearing (e.g.,

increased damping, backlash, acoustic noise, and reflected inertia, which scales with the transmission ratio squared) [9]. Gears also have torque-dependent friction that further increase impedance and reduce backdrivability and efficiency [8]. For wearable robotics with high output impedance, the external loads experienced during daily locomotor activities might be insufficient to overcome the impedance to backdrive the actuator. These characteristics of highly-geared motor-transmission systems can impede dynamic physical interactions between the human and robot and between the robot and environment, which can especially encumber persons with partial motor control function (e.g., elderly and/or those with osteoarthritis or poststroke) who may benefit from the ability to backdrive the joints and actively participate in locomotion. Here backdrive torque is defined as the minimum torque needed to overcome the actuator impedance (i.e., reflected inertia and friction) to backdrive the motor through its transmission.

Compared to traditional rigid actuators used in robotics, backdriveable actuators with low impedance transmissions have many benefits for control and efficiency, including: 1) free-swinging dynamic leg motion similar to passive prosthesis, which can simplify the control during swing phase and allow for more natural, energy-efficient locomotion, 2) compliant foot-ground impacts, 3) negligible unmodeled actuator dynamics, which can further simplify the control, 4) intrinsic backdriveability comparable to series elastic actuators without their design and manufacturing complexities and low bandwidth, and 5) energy regeneration [48]. Energy regeneration is the process of converting some of the otherwise dissipated energy during periods of negative mechanical work into electrical energy via backdriving the actuator (Fig. 1). In other words, when backdriven by an external load, the

motor can provide a braking torque to decelerate the load (e.g., motion control during swing phase) while concurrently generating electricity [15, 50-51]. This is similar to regenerative braking in electric and hybrid electric vehicles.

During standard forward operation, an electric motor converts electrical power (P_e) into mechanical power (P_m) such that the mechanical power output $\{P_m = \tau_j \dot{\theta}_j\}$ is the product of the joint torque (τ_j) and angular speed $(\dot{\theta}_j)$ and the electrical power input $\{P_e = i_m v_M\}$ is the product of the motor winding current (i_m) and voltage (v_m). When backdriven by an external load, the motor can operate like a generator, converting mechanical power into electrical power. The actuator efficiency (η_a) during forward operation is the ratio of electrical-to-mechanical power conversion $\left\{\eta_a = \frac{1}{T}\left(\frac{\int \tau_j \dot{\theta}_j dt}{\int i_m v_m dt}\right) \times 100\%\right\}$ and vice-versa for energy regeneration when backdriven. Assuming a sufficient motor driver to control bidirectional power flow during motoring and braking operations, the regenerated energy could be used for battery recharging and/or transferred to other joints to support positive power generation. Backdriveable actuators with energy regeneration can thus help extend the battery-powered autonomy and/or decrease the weight of the onboard batteries.

The MIT Cheetah was one of the first legged robots to use backdriveable actuators with energy regeneration [48, 52-55]. The robot was designed with torque-dense motors, low gearing, regenerative motor drivers, and low leg mass and inertia. The motor torque density was increased by increasing the gap radius, which is the radius of the gap between the stator windings and permanent magnets on the rotor. The low-ratio transmission (6:1) allowed for efficient bidirectional power flow between the motor and end effector. The forward and backdrive directional efficiencies of the transmission were 98% and 96%,

respectively, the differences of which were attributed to asymmetric friction and viscous damping losses [52]. The actuator backdrive efficiency was ~63% [48]. The MIT Cheetah achieved a cost of transport of ~0.5 such that the 33-kg robot can run at 6 m/s while consuming 973 W of electrical power [48]. Approximately 76% of the power losses (P_{loss}) were attributed to Joule heating, which is expressed by $\{P_{loss} = i_m^2 R_m\}$, where R_m is the resistance of the motor windings. To improve accessibility of these high-performance actuators for legged locomotion, [56] recently proposed an open-source, 3D-printed design.

Taking inspiration from the MIT Cheetah, [57-63] applied similar design principles to wearable robotics to achieve a low impedance, high backdriveable interface between the human and robot. They designed pancake-style brushless DC motors with encapsulated windings for high torque-density. The large diameter of the motor allowed for a low-ratio transmission (7:1) to be integrated inside the stator for a low form factor [58]. Benchtop and human walking experiments with a robotic exoskeleton showed that the actuator could generate 20-24 Nm of peak output torque and 1-3 Nm of backdrive torque [57-60, 63], thus providing a high torque output during stance phase and a low backdrive torque during swing phase. Their backdriveable actuators also allowed for energy regeneration and sharing between joints for improved locomotor efficiency [61]. To date, these wearable robotic systems are some of the few to demonstrate both power generation and regeneration during walking. Other examples of robotic leg prostheses and exoskeletons using backdriveable actuators include [64-68].

One of the biggest limitations to energy regeneration is the relatively low efficiency of most motor-transmission systems [11]. Two of the leading sources of energy losses are Joule heating in the motor windings and friction in the transmission [8-9]. High transmission ratios can reduce the motor torque needed for legged locomotion, thus decreasing the motor current and the associated Joule heating losses. However, high gearing can also increase weight, friction, and reflected inertia, which increases impedance and reduces backdrivability and the potential for energy regeneration [9]. Alternatively, high torque-density motors can decrease the needed transmission ratios by generating high output torque, thereby circumventing the inefficiencies of high gearing, although at the expense of more winding current and thus higher Joule heating losses [8]. An open challenge for the research community is to optimize the tradeoff between the actuator output torque and backdrive torque. Many system design parameters can affect this tradeoff (e.g., transmission ratio and efficiency, motor terminal resistance, and motor torque and speed constants) [8]. Given the complex interactions between these different parameters, determining the optimal actuator design via experimental trial-and-error can be difficult. Modelling and simulation can be used to co-optimize the motor and transmission system design parameters to optimize bidirectional efficiency (including energy regeneration) and the actuator dynamics [69-70].

Despite the benefits of backdriveability via quasi-direct drives, high-torque motors tend to 1) require specialized motor drivers for real-time commutation and control, 2) have problems with thermal overheating due to difficulty evacuating heat, and 3) have higher motor mass and inertia due to the larger diameter [14].

2.3.2 Energy Regeneration

While the aforementioned robotic systems focused on backdrivability, a byproduct of which is improved efficiency and the potential for energy regeneration, other systems have been designed specifically for regenerative braking, as reviewed in our previous work [15]. For example, the knee exoskeleton by Donelan and colleagues [71–75] was designed to convert human biomechanical power into electrical power without requiring significant metabolic effort. They used a 113:1 geared transmission and brushless DC generator to harvest energy during late swing knee extension such that the motor assisted the muscles to decelerate the swing leg prior to heel strike, therein minimizing the metabolic cost of operating the muscles as biological brakes, while concurrently generating electricity. The mechanical-to-electrical power conversion efficiency of the actuator was ~63% [74]. The system performance was evaluated using cost of harvesting (COH), which is the additional metabolic effort needed to generate electrical power $\left\{COH = \frac{\Delta metabolic\ power}{\Delta electrical\ power}\right\}$. When walking at 1.5 m/s, users were able to generate 4.8 ± 0.8 W of electricity with a 5 ± 21 W increase in metabolic power consumption compared to walking with the system but not generating electricity, therein yielding a cost of harvesting of 0.7 ± 4.4 W [74]. This knee exoskeleton could be worn on the unaffected limb of persons with unilateral impairments to help recharge a robotic leg prosthesis or exoskeleton worn on the contralateral affected limb.

More recently, a collaborative research group [76-90] published a series of studies on modeling, optimization, and control of robotic and prosthetic systems with energy regeneration. They used biogeography-based optimization to search for the optimal design

and control parameters that maximized both energy regeneration and reference tracking motion control. A Pareto front was used to evaluate the trade-off between the two objective functions such that a higher impedance system tends to yield more accurate motion tracking but less energy regeneration. For example, their multi-objective optimization in [83] resulted in 0.9° of root mean square tracking error relative to reference joint kinematics while regenerating ~53 J of electrical energy over 5-second computer simulations of human-prosthesis walking. The energy regeneration efficiency was 30%. A unique feature of their research was the use of ultracapacitors for storing the regenerated energy.

Most robotic leg prostheses and exoskeletons are powered by lithium-polymer or lithium-ion batteries [1, 4]. Batteries tend to have a high energy density (e.g., ~100 Wh/kg), which allows for extended operation, but a low power density (e.g., 0.1-1 kW/kg), which yields slow charge and discharge rates [91]. However, in many mechatronics applications, the rate at which mechanical energy should be converted into electrical energy for regenerative braking is higher than the rate at which most batteries can absorb energy [79]. In other words, rechargeable batteries tend to have insufficient power densities. In contrast, ultracapacitors have a high-power density (e.g., ~10 kW/kg) but low energy density (e.g., 1-10 Wh/kg), can charge and discharge at high rates without damage, and have almost infinite lifecycles [91]. Ultracapacitors bridge the gap between conventional capacitors [92–94] and batteries. Although the total energy stored per unit mass in ultracapacitors is typically much smaller than batteries, recent breakthroughs in nanotechnology are enabling the fabrication of graphene-based ultracapacitors, which

have reached energy densities of ~64 Wh/kg [81]. Regenerative systems for robotic leg prostheses and exoskeletons could include an ultracapacitor, for fast charging and discharging, and a rechargeable battery, for extended operation.

2.4 Applications

Despite these developments in energy-efficient actuators for wearable robotics, previous studies have focused on steady-state level-ground walking – e.g., energy regeneration [34, 71-74, 76, 79, 82-87, 89, 95-100] and mechanical energy storage and return [17-18, 31, 34, 38-43, 45-46]. In real-world community mobility, however, steady-state locomotion is generally short lived and separated by frequent transitions between different states (e.g., ~40% of walking bouts are less than 12 consecutive steps) [101]. This observation is supported by [102-103], which recently showed that a relatively small percentage (~8%) of real-world walking environments consist of continuous level-ground terrain. Targeted users of wearable robotic systems (i.e., older adults and/or persons with physical disabilities) also tend to walk slower and take fewer steps per day. For example, self-selected walking speed and daily step count have been shown to decrease by 24% from 25 to 75 years age and by 75% from 60 to 85 years age, respectively [104].

These differences, especially in walking speed, can have implications for energy recycling. Studies of robotic leg prostheses and exoskeletons with regenerative actuators have shown a positive correlation between walking speed and both energy regeneration and efficiency (i.e., faster walking generates more electricity and more efficiently) [61, 73-75, 89, 95-96, 105]. For a given back electromotive force (EMF) constant, an electric motor generates a voltage proportional to its rotational speed. Slower walking would backdrive

the actuator with lower speeds and thus generate less electricity. Motors are also generally less efficient when generating torques at low speeds due to Joule heating. A recent study by [61] showed that increasing walking speed with a robotic knee-ankle prosthesis from 0.9 m/s to 1.6 m/s increased the actuator power conversion efficiency from 40% to 59%. [105] also showed that the ratio of regenerated energy to total power consumption using a robotic ankle prosthesis increased from 27% to 35% when walking speed increased from 0.7 m/s to 1.3 m/s. Although several studies have recently simulated energy regeneration in human-exoskeleton systems during stand-to-sit movements [106-107] and walking on variable slopes and speeds [108], these studies were limited by model assumptions and lacked experimental validation. Moving forward, designers should consider energy regeneration, as well as mechanical energy storage and return, during locomotor activities of daily living besides steady-state level-ground walking.

3. CONCLUSION

In this study, we reviewed two of the leading energy-efficient actuator design principles for legged and wearable robotic systems: series elasticity and backdrivability. Our goal is to inform next-generation designers of robotic leg prostheses and exoskeletons of the state-of-the-art in energy-efficient actuators for human-robot locomotion. As shown by inverse dynamic simulations of walking, there are periods of negative joint mechanical power and work that can be used to improve efficiency by recycling some of the otherwise dissipated mechanical energy using series elastic actuators and/or backdriveable actuators with energy regeneration. Compared to traditional highly-geared motor-transmission systems used in robotics, series elastic actuators can improve shock tolerance during foot-

ground impacts and reduce the peak power and energy consumption of the electric motor via mechanical energy storage and return using a passive elastic element, the performance of which is dependent on the spring design. However, actuators with series elasticity tend to have lower output torque, increased mass and architecture complexity due to the added physical spring, and limited force and torque control bandwidth.

High-torque density motors with low-ratio transmissions, known as quasi-direct drives, can likewise achieve low output impedance and high backdrivability, therein allowing for dynamic physical interactions, in addition to energy regeneration (i.e., the conversion of mechanical energy into electrical energy via backdriving the motor). However, torque-dense motors tend to have higher Joule heating losses due to higher current draw, greater motor mass and inertia, and require specialized motor drivers for real-time commutation and control. Quasi-direct drives are also typically more expensive than traditional motor-transmission systems.

Although energy-efficient actuators can help extend the battery-powered autonomy and/or decrease the weight of the onboard batteries, most robotic leg prostheses and exoskeletons that have been designed for efficiency have been limited to steady-state level-ground walking. However, targeted users of these wearable robotic systems (e.g., older adults and/or persons with physical disabilities) often walk slower and take fewer steps per day. Moving forward, designers should consider energy regeneration, and mechanical energy storage and return, during locomotor activities of daily living besides continuous level-ground walking. In addition to robotic leg prostheses and

exoskeletons, these energy-efficient actuator design principles can also be applied to humanoids and autonomous walking robots.

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Figure Captions List

Fig. 1 The average hip, knee, and ankle joint mechanical power (W/kg) per stride in healthy young adults (n=10) walking at 1 m/s on level-ground and normalized to total body mass (top left). The positive and negative values represent joint power generation and absorption, respectively. Data were calculated from [28], the trajectories of which begin and end with heel-strike (top right). These joint mechanical energetics have implications on the energy-efficient actuation of robotic leg prostheses and exoskeletons (bottom left); the nomenclature are described in the text.

Fig. 2 Examples of robotic leg prostheses and exoskeletons with series elastic actuators (two images on the left) and backdriveable actuators with low impendence transmissions (two images on the right). The photographs (left to right) were provided by Tom Verstraten [39], Elliot Rouse [41], and Robert Gregg [61, 63].

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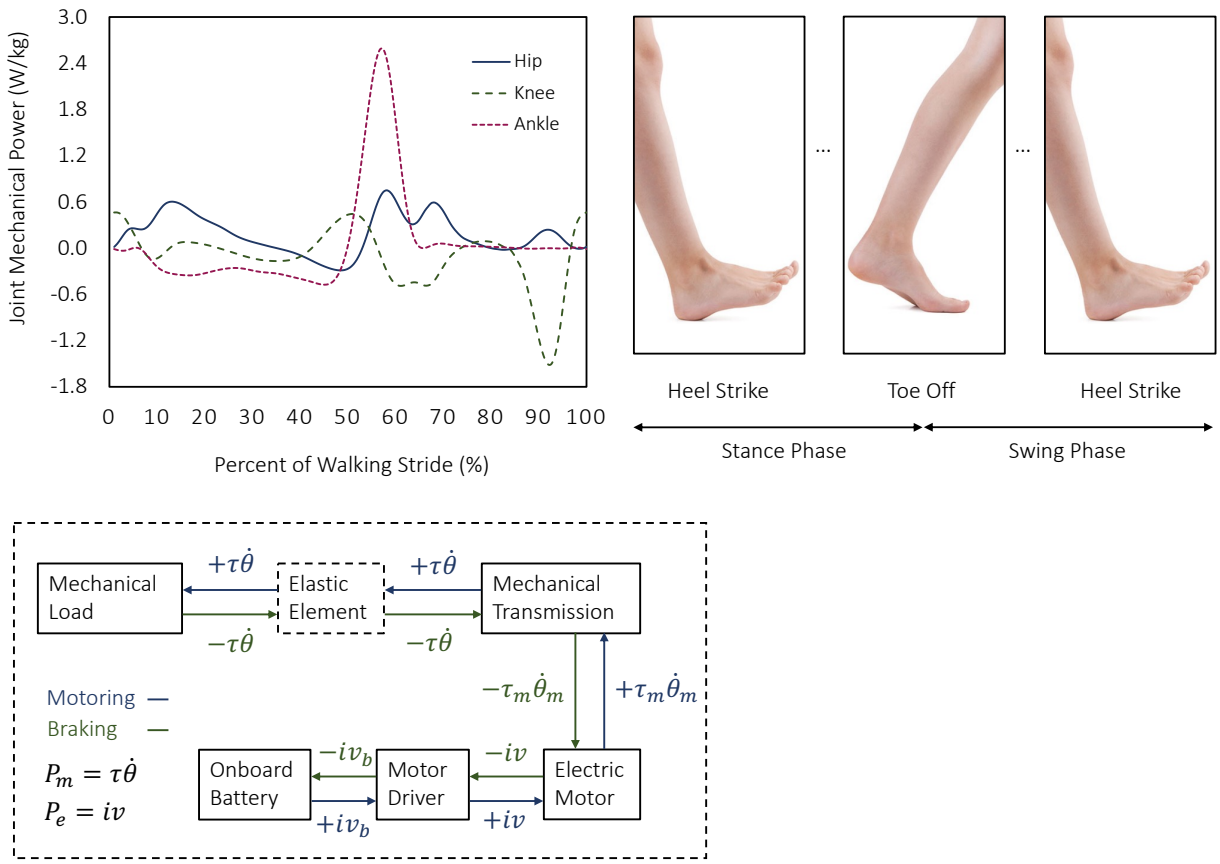

Fig. 1 The average hip, knee, and ankle joint mechanical power (W/kg) per stride in healthy young adults (n=10) walking at 1 m/s on level-ground and normalized to total body mass (top left). The positive and negative values represent joint power generation and absorption, respectively. Data were calculated from [28], the trajectories of which begin and end with heel-strike (top right). These joint mechanical energetics have implications on the energy-efficient actuation of robotic leg prostheses and exoskeletons (bottom left); the nomenclature are described in the text.

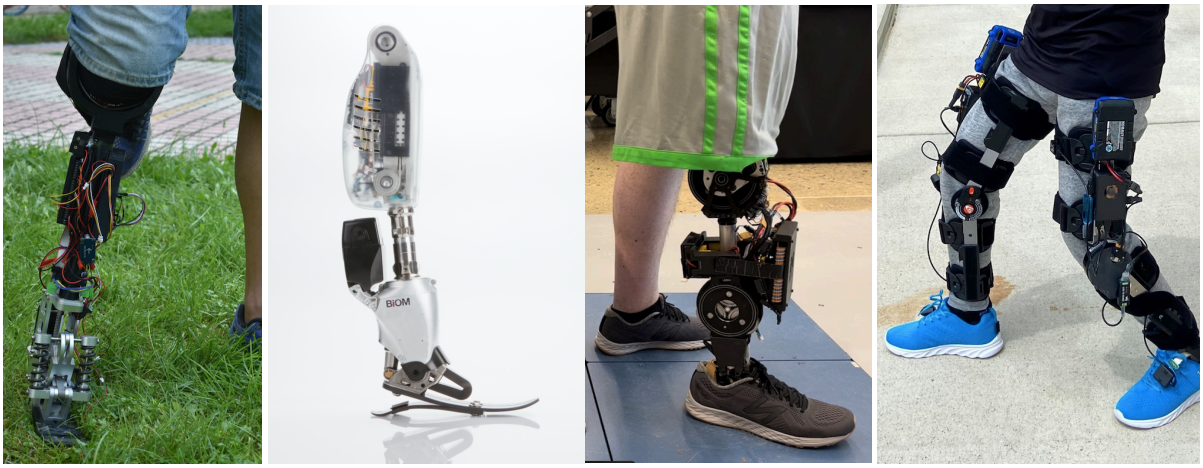

Fig. 2 Examples of robotic leg prostheses and exoskeletons with series elastic actuators (two images on the left) and backdriveable actuators with low impendence transmissions (two images on the right). The photographs (left to right) were provided by Tom Verstraten [39], Elliot Rouse [41], and Robert Gregg [61, 63].

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