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# Lower-Limb Prostheses and Exoskeletons with Energy Regeneration: Mechatronic Design and Optimization Review

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## ABSTRACT

*Lower-limb biomechatronic devices (i.e., prostheses and exoskeletons) depend upon onboard rechargeable batteries to power wearable sensors, actuators, and microprocessors, therein inherently limiting their operating durations. Regenerative braking, also termed electrical energy regeneration, represents a promising solution to the aforementioned shortcomings. Regenerative braking converts the otherwise dissipated mechanical energy during locomotion into electrical energy for recharging the onboard batteries, while simultaneously providing negative mechanical work for controlled system deceleration. This paper reviewed the electromechanical design and optimization of lower-limb biomechatronic devices with electrical energy regeneration. The technical review starts by examining human walking biomechanics (i.e., mechanical work, power, and torque about the hip, knee, and ankle joints) and proposes general design principles for regenerative braking prostheses and exoskeletons. Analogous to electric and hybrid electric vehicle powertrains, there are numerous mechatronic design components that could be optimized to maximize electrical energy regeneration, including the mechanical power transmission, electromagnetic machine, electrical drive, device mass and moment of inertia, and energy storage devices. Design optimization of these system components are individually discussed while referencing the latest advancements in robotics and automotive engineering. The technical review demonstrated that existing systems 1) are limited to level-ground walking applications, and 2) have maximum energy regeneration efficiencies between 30-37%. Accordingly, potential future directions for research and innovation include 1) regenerative braking during dynamic movements like sitting down and slope and staircase descent, and 2) utilizing high-torque-density electromagnetic machines and low-impedance mechanical power transmissions to maximize energy regeneration efficiencies.*

*Keywords: Actuators and Transmissions, Medical Robotics, Multi-Body Dynamics and Exoskeletons, Prosthetics, Wearable Robots*

## 1. INTRODUCTION AND BACKGROUND

Despite promising technological advancements in lower-limb prostheses and exoskeletons, the widespread utility of these wearable biomechatronic devices remains fundamentally dependent upon untethered power sources. Electromechanical lower-limb prostheses and exoskeletons have traditionally required significant amounts of electrical energy to power onboard sensors, actuators, and microprocessors during human locomotion [1-3]. Electrical energy has been provided through rechargeable lithium-polymer and lithium-ion batteries [1, 3-7]. Considering the geometric and mass constraints of biomimetic limb designs, the finite energy densities of rechargeable batteries and the significant energy requirements of electromechanical systems have brought about two prominent shortcomings compared to conventional passive devices: increased weight and limited operating durations [2-3, 7-12].

Most electromechanical lower-limb prostheses and exoskeletons have required frequent recharging [1, 3, 6, 8]. For instance, the semi-powered Össur Rheo Knee (Iceland) and Ottobock C-Leg (Germany) require recharging approximately every 36 hours [13-14]. The Össur Power Knee, the only commercially-available powered lower-limb prosthesis, provides between 5-7 hours of continuous operation, depending upon the activity usage [4, 14-15]. A recent technical review from Laschowski and Andrysek [4] noted that amputee patients across numerous studies generally preferred semi-powered lower-limb prostheses over the Össur Power Knee. Subjective feedback indicated that the Power Knee’s substantial weight and limited battery lifespan were the main deterrents to continued usage [4]. Most powered lower-limb exoskeletons have provided 1-5 hours of maximum operation [6]. Consequently, further advancements in untethered power sources for lower-limb biomechatronic devices are needed.

Biomechanical energy harvesting represents a promising solution to the aforementioned shortcomings. Biomechanical energy harvesting involves converting the otherwise dissipated mechanical energy during human locomotion into electrical energy for recharging the onboard batteries [14, 16]. Such energy regeneration technology can reduce the onboard battery weight and/or extend the operating durations between recharging, thereby enabling patients to ambulate longer distances and have greater independence [6-7, 15-17]. Humans expend approximately 10.7 MJ of metabolic energy each day, resembling the amount of energy stored in 800 AA (2500 mAh) batteries weighing approximately 20 kg [14]. Notable advances in biomechanical energy harvesting, particularly with semi-powered lower-limb exoskeletons for able-bodied individuals, have come from Donelan and colleagues [13, 16-19]. Their exoskeletons empirically demonstrated maximum energy regeneration efficiencies (i.e., percentage of mechanical energy converted into electrical energy) around 63% [18]. Several investigations have recently considered incorporating electrical energy regeneration into lower-limb prostheses and exoskeletons for geriatrics and rehabilitation patients (i.e., individuals with lower-limb amputation, stroke, and spinal cord injury). To increase the familiarity and subsequent application of these wearable biomechatronic devices for clinical applications, the objective of the following technical review was to examine the electromechanical design and optimization of lower-limb prostheses and exoskeletons with electrical energy regeneration.

Literature searches were conducted in prominent scientific and engineering databases, including: IEEE Xplore, ProQuest, Web of Science, MEDLINE, Scopus, EMBASE, and PubMed. Keywords included: prostheses, prosthetics, exoskeletons, energy regeneration, regenerative braking, biomechanical energy harvesting, power generation, backdrivable, four-quadrant operation, and human-powered devices. The technical review focused on publications written in English and published in peer-reviewed journals and conferences between 1980-2018. Regenerative systems encompassing only mechanical energy storage (e.g., elastic elements [20-22], hydraulic accumulators [23], and rotating flywheels [24]) and those situated external to lower-limb systems (e.g., electricity-generating backpacks [25]) were excluded. Mechanical energy storage devices were excluded because such devices generally contain lower energy densities than those involving electrochemical energy storage [26]. The technical review was organized into the following sections: human walking biomechanics and the prospective applications of regenerative braking, system design and optimization of regenerative powertrains, examples of lower-limb biomechatronic devices with electrical energy regeneration, and potential future directions for research and innovation.

## 2. HUMAN-POWERED DEVICES

Early biomechanical energy harvesting devices focused on generating electricity during heel-strike via compressing shoe-integrated generators comprising piezoelectric materials or electroactive polymers [5, 27]. These generators harvested between several microwatts and milliwatts of maximum electrical power during level-ground walking [5,

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13-14, 25, 27], rendering them insufficient for recharging many lower-limb biomechatronic devices considering that existing powered knee prostheses consume 43 ± 30 W of average maximum electrical power during human locomotion [4]. Conversely, rotational electromagnetic generators affixed to lower-limb joints have the potential to regenerate several watts of electricity [28]. For optimal design and control of such electromagnetic-based regenerative powertrains, an evaluation of human walking biomechanics is first warranted.

**2.1 Human Walking Biomechanics**

Human joints perform both negative mechanical work (i.e., braking) and positive mechanical work (i.e., motoring). The resultant joint torque and rotational velocity have opposing polarities during braking, and the same polarities during motoring [14, 29-30]. Note that the human musculoskeletal system generates mechanical energy from chemical (food) energy with maximum efficiencies around 25%, resembling that of many internal combustion engines [13, 16]. Table 1 presents standard quantities of mechanical work, power, and torque about the ankle, knee, and hip joints during 1 m/s level-ground walking (i.e., comprising representative speeds of geriatrics and rehabilitation patients) [1, 8, 20-24, 30].

Mechanical power was computed from the resultant joint torques and rotational velocities and numerically integrated over time to determine joint biomechanical energy. Compared to the ankle (28%) and hip (19%), the knee joint produces the most negative mechanical work (92%) (see Table 1) [5, 14, 29-30]. These quantities represent intra-joint percentages of negative mechanical work. The ankle joint generates the most positive mechanical power [30]. The maximum resultant joint torques about the ankle are approximately 3.5 times greater than those about the knee (see Table 1). During level-ground walking, the human knee joint primarily resembles a damper mechanism, performing negative mechanical work through energy dissipation, and the ankle joint mainly resembles an actuating motor, performing positive mechanical work and generating forward propulsion.

Early research from Winter [29-30] identified four biomechanical states of the human knee joint during level-ground walking, including: energy dissipation following heel-strike (quadrant 1), energy generation during mid-stance (quadrant 2), energy dissipation around early-swing (quadrant 3), and energy dissipation during late-swing (quadrant 4). Only the latter state concerns the knee joint flexor actuators. These characteristic human walking biomechanics are illustrated schematically in Fig. 1. Note that the "extension" and "flexion" terminology in Fig. 1 describe the resultant mechanical work from the knee joint extensor and flexor actuators, respectively. Most negative mechanical work, and therefore energy dissipation, occurs during late-swing [29-30]. The amount of negative work performed during late-swing is less dependent upon the knee joint rotational velocity than other locomotion states. For example, reducing average walking velocity from 1.5 m/s to 1.0 m/s decreased the late-swing and early-stance negative work quantities by 19% and 56%, respectively [13]. Consequently, many knee-centered biomechanical energy harvesting devices have focused on generating electricity specifically throughout late-swing [8, 13-16, 18-19, 31-32].

**2.2 Regenerative Braking**

Taking into consideration the aforementioned human gait biomechanics, most knee prostheses and exoskeletons have incorporated energy dissipating mechanisms to achieve biomimetic swing and stance control, including mechanical friction and hydraulic and pneumatic-based dampers [1, 6, 8, 33]. Rather than dissipating the mechanical energy as heat, said energy could instead be converted into electricity using an electromagnetic generator for recharging the onboard batteries, while simultaneously providing negative mechanical work for controlled system deceleration [11, 13, 15, 31, 33-37]. Such energy-efficient mechatronic designs resemble regenerative braking in electric and hybrid electric vehicles, which utilize electrical drives to digitally control the actuation system during motoring and braking operations [11, 15, 18, 26, 33, 37-41]. Together with innovations in automotive regenerative braking, operational ranges of electric vehicles have increased approximately 450% since the 1980s [9]. Accordingly, similar increases in operating durations might be achievable with lower-limb biomechatronic devices. Although similar to regenerative braking, dynamic braking involves dissipating the regenerated electrical energy using onboard resistors.

For optimal design of lower-limb prostheses and exoskeletons with electrical energy regeneration, the knee joint demonstrates more applicable/advantageous biomechanics during level-ground walking than the ankle and hip joints. Considering the human knee joint performs the most negative mechanical work and undergoes the lowest resultant joint torques (see Table 1), knee-centered designs theoretically enable higher mechanical-to-electrical energy conversion and alleviate the demand for heavier mechanical power transmissions, respectively [14, 19, 33]. Coincidentally, few

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mechatronic ankle prostheses and exoskeletons have included electrical energy regeneration [42].

## 3. SYSTEM DESIGN AND OPTIMIZATION

Analogous to electric and hybrid electric vehicle powertrains [26, 40-41], there are numerous mechatronic design configurations that could facilitate regenerative braking in lower-limb prostheses and exoskeletons. The mechanical power transmission, electromagnetic machine, electrical drive, device mass and moment of inertia, and energy storage devices each represent several system components that could be optimized to maximize electrical energy regeneration without adversely affecting human walking biomechanics [1, 9, 13-14]. Previous research has indicated that maximum energy regeneration and reference joint biomechanics tracking are conflicting objective functions [43].

### 3.1 Mechanical Power Transmissions

Human walking involves relatively slow lower-limb joint rotational velocities (e.g., approximately 20 rpm) [14]. In contrast, electromagnetic machines generally operate most efficiently at higher rotational velocities (e.g., 1000-10,000 rpm) [5, 14, 22, 31]. Mechanical power transmissions, like gear mechanisms and harmonic drives, can increase the lower-limb joint rotational velocities to those more suitable for electromagnetic machines, therefore enhancing power conversion [14, 17, 28, 44-46]. Transmission parameters like gear ratio and energy efficiency should be incorporated into the system design optimization [7, 10, 13, 45-49]. Although high transmission ratios might be considered favorable for such biomechatronic applications, increasing the

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number of gear train stages, for instance, decreases the transmission efficiency through higher friction and increases the mechanism weight and mechanical impedance [10, 13-14, 45-46, 48-49]. Increasing the number of gear train stages moreover increases the mechanical backlash and structural complexity [43]. Higher transmission ratios within one stage might be more advantageous than distributing them across multiple stages [46]. Nevertheless, the gear diameters within one stage cannot be designed arbitrarily wide considering the geometric constraints of lower-limb systems [13].

Compared to gear mechanisms, which contain fixed transmission ratios, continuously variable transmissions might produce more efficient energy regeneration [3, 7, 22]. Human lower-limb joint rotational velocities can vary significantly within given ambulatory movements [3, 7]. Nevertheless, electromagnetic machines generally operate most efficiently at constant velocities [14]. Continuously variable transmissions can vary the transmission ratios to maintain constant rotational velocities of electromagnetic machines, and therefore optimal efficiency, despite variations in mechanical inputs [3, 7, 14, 22]. Previously reported continuously variable transmission designs have achieved maximum energy efficiencies above 90% [22]. Such automatic power transmissions were originally designed for motorized vehicle applications to enhance fuel economy by maintaining optimal transmission ratios across varying operating conditions. Apart from varying the transmission ratios continuously within given ambulatory movements (i.e., using continuously variable transmissions), actively variable transmissions could be utilized to change the transmission ratios when

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transitioning between ambulatory movements with different speed-torque requirements [3, 7].

### 3.2 Electromagnetic Machines

Electromagnetic motors convert electrical energy into mechanical energy. When backdriven, motors operate as electromagnetic generators, converting mechanical energy into electrical energy [36, 41, 50-51]. Most powered lower-limb prostheses and exoskeletons have been motorized with direct current (DC) electromagnetic machines, specifically permanent-magnet brushed and brushless DC motors [3-4, 6-7, 42, 52-57]. For brushless DC motors, the permanent magnets and windings are situated on the rotational and stationary elements, respectively [57]. The opposite holds for brushed DC motors, wherein the electromotive forces (i.e., voltages) are produced within electrical conductors (i.e., armature windings) rotating inside a permanent magnetic field. When the armature windings are connected to an electrical load, current subsequently flows and generates electricity [11, 17]. Brushless DC motors are generally more energy-efficient (85-90%) than brushed DC motors (75-80%) and have higher power densities, which might explain their growing implementation among robotics and biomechatronic systems [57]. Brushed DC motors, together with harmonic drives, have demonstrated maximum power densities ranging between 200-300 W/kg [10]. In comparison, human muscle actuators have maximum power densities around 500 W/kg [10].

Many electrical and mechanical parameters of electromagnetic machines can be incorporated into the system design optimization to maximize electrical efficiency, including: the motor constant, motor torque constant, armature winding resistance and

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inductance, back electromotive force constant, maximum rated torque and rotational velocity, and rotor moment of inertia [9, 13, 38, 45, 47-48, 58]. Note that the back electromotive force constant corresponds with the motor velocity constant. Although the aforementioned parameters are predetermined from the manufacturer, system optimization for electrical efficiency could assist with machine selection. Recent research involving regenerative braking lower-limb prostheses advocated for selecting electromagnetic machines with high motor constants and/or low armature winding resistances to decrease the needed transmission ratios [47].

**3.3 Electrical Drive Systems**

Electrical drives are commonly employed for controlling electromagnetic machines. These intelligent control systems incorporate microprocessor controllers, onboard sensors, and power modulating circuits. Figure 2 presents an example electrical drive system. By digitally controlling the electrical energy entering and leaving the electromagnetic machine, electrical drives 1) provide safeguards against short-circuiting, and 2) indirectly control the rotor torque, rotational velocity, and direction of rotation [39]. Contrasting automotive systems which initiate regenerative braking via manually pushing the brake pedal, control systems of lower-limb prostheses and exoskeletons must automatically determine the motoring and braking periods [13, 18-19]. Onboard sensors like inertial measurement units [3, 7, 52-53] and rotary encoders [31, 53, 55] measure the system operation and provide closed-loop feedback to the microprocessor controller [31-32, 46, 55]. Error between the experimental and reference quantities are

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computed and typically entered into a proportional-integral-derivative (PID) controller, which outputs control commands to the power modulators [39].

Utilizing instructions from the embedded controller, the power modulating circuit 1) digitally controls the frequency and amplitude of electrical energy between the electromagnetic machine and energy storage devices, and 2) converts between alternating and direct current waveforms when needed [28, 39]. Power modulators in lower-limb biomechatronic devices with energy regeneration have mainly comprised H-bridge electrical circuits [2, 9, 11, 36, 53, 55, 59]. Other preferential circuits have included voltage source converters and buck-boost converters [9, 38-39, 43]. Metal-oxide-semiconductor field-effect transistors (MOSFETs) are frequently implemented for electrical amplifiers and switches [8, 11, 38, 44, 53]. MOSFETs are voltage-controlled switches that consume minimal electrical energy, making them appropriate for battery-powered biomechatronics. Generally speaking, regenerative braking systems include bidirectional power modulators that facilitate four-quadrant operation of electromagnetic machines, including: forward braking, forward motoring, reverse motoring, and reverse braking [3, 7, 9, 31, 37-39, 41, 44, 59]. For additional information on the aforementioned electrical drive elements, the authors recommend the electronics engineering textbook from Wildi [60].



**3.4 Device Mass and Moment of Inertia**

Design engineers should take into consideration how, when compared to conventional lower-limb prostheses and exoskeletons, carrying specialized regenerative braking components (e.g., the mechanical power transmission and/or electromagnetic machine) affect human metabolic power [14-15]. The energy efficiencies of such biomechatronic systems could be characterized via the relationship between changes in electrical energy and changes in metabolic energy, specifically the differences in metabolic energy expenditure while ambulating with and without the specialized regenerative components [14]. Notable design parameters theoretically affecting human metabolic power include device mass and moment of inertia about biological joints [3, 7, 10, 14, 45-46, 49].

Human gait experiments have demonstrated that carrying additional weight more distally on the lower-limbs generally coincides with higher metabolic energy expenditure [3, 7, 10, 13-15, 46, 61-62]. Design optimization for system energy efficiencies should consider minimizing device mass and moment of inertia about biological joints [3, 7, 10, 13-15, 28, 45-46, 49, 61-62]. Minimizing such inertial parameters would be particularly important when designing pediatric biomechatronic devices, considering the unique geometric and weight constraints [63-64]. Furthermore, relating to socket-suspended lower-limb prostheses, minimizing the device weight would theoretically decrease musculoskeletal pain occurrences associated with excessive tugging (tension forces) on the prosthesis-residuum interface [3, 65]. Note that prospective reductions in battery weight from incorporating electrical energy regeneration would, to some extent, counterbalance the added weight of the regenerative components [33]. Minimizing device mass and moment of inertia would moreover decrease the corresponding electromagnetic machine torque requirements. Lightweight composite materials could be utilized for the chassis and mechanical power

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transmission designs to minimize device weight [3, 14, 28, 45]. To the authors' knowledge, previous investigations have not evaluated the metabolic effects of carrying specialized regenerative braking components with geriatrics and rehabilitation patients.

**3.5 Energy Storage Devices**

Many lower-limb prostheses and exoskeletons have incorporated mechanical energy storage and return systems, including elastic elements [6, 20-22, 31, 50, 55-56, 62], hydraulic accumulators [6, 23], and rotating flywheels [24]. Storing energy mechanically during human locomotion circumvents the inefficiencies associated with energy domain conversion (i.e., mechanical to electrochemical, back to mechanical) [22]. Nevertheless, incorporating elastic elements can significantly increase the complexity of the system dynamics and control [45, 49] and increase the overall mechanism weight. Conversely, electrochemical energy storage devices generally have higher energy densities (e.g., 108-190 Wh/kg) than those involving mechanical energy storage (e.g., less than 10 Wh/kg) [4, 26]. Most powered lower-limb prostheses and exoskeletons have used rechargeable lithium-polymer or lithium-ion batteries [3-4, 6-7, 31, 52-56, 62]. For biomechanical energy harvesting during level-ground walking, the rates at which mechanical energy should be converted for effective system deceleration are higher than those associated with battery recharging [2, 47, 59]. Accordingly, energy storage devices with faster charging and discharging rates are warranted.

Electrochemical double-layer capacitors, also termed ultracapacitors or supercapacitors, represent an emerging energy storage method utilized in mechatronics engineering. Ultracapacitors are designed for maximum power densities [2, 26, 34, 47, 51, 57-59, 66-67]. Their low internal resistances permit rapid charging and discharging, with maximum bidirectional electrical currents of approximately 1000 A [35]. Ultracapacitors are becoming increasingly lightweight and inexpensive [2, 35, 51, 57, 59, 67]. These design features might explain their growing implementation among robotics and automotive systems with electrical energy regeneration [26, 35, 38, 40, 51, 57-59, 66, 68-69]. Although conventional ultracapacitors contain low energy densities relative to electrical batteries, recent breakthroughs in nanotechnology are enabling the fabrication of graphene-based ultracapacitors, which have attained energy densities of approximately 64 Wh/kg [35, 59]. An optimal energy storage system for lower-limb biomechatronic devices might include both ultracapacitors, for rapid charging and discharging, and electrical batteries, for extended operation [57-59].

**4. REPRESENTATIVE BIOMECHATRONICS RESEARCH**

The following examples represent the majority of research publications pertaining to lower-limb biomechatronic devices with electrical energy regeneration. Although other lower-limb prostheses have included electrical drives with four-quadrant operation, specifically those from Goldfarb's group [32, 52-54], Lenzi's group [7], and Herr's group [22, 31, 42, 55-56], limited information regarding their electricity generation capabilities have been disseminated. Furthermore, while the lower-limb exoskeletons from Goldfarb and colleagues [70-79], Rouse and colleagues [61-62], and Gregg and colleagues [45, 49] have comprised backdrivable actuator-transmission systems, and therefore capable of regenerative braking, such biomechatronic devices have not explicitly demonstrated electrochemical energy storage and regeneration.

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### 4.1 Example 1: Powered Lower-Limb Prosthesis Design

The earliest documented powered lower-limb prosthesis with electrical energy regeneration originated from Flowers's and colleagues during the 1980s [33-34, 36, 43]. Different combinations of belt drives, magnetic-particle brakes, gears, and linkage mechanisms encompassed the mechanical power transmission [33-34, 43]. The actuation and electrical drive systems included a permanent-magnet DC machine and bidirectional pulse-width modulated power converters, respectively [33-34, 43]. The switching converters comprised H-bridge electrical circuits containing MOSFETs [33]. The microprocessor controller utilized feedback from onboard optical encoders and torque transducers [33, 43]. Electrolytic capacitors provided electrical energy storage [33-34, 43].

Computational methods were used to optimize the mechanical power transmission design, device weight, and permanent-magnet DC machine parameters [33-34, 43]. The optimization objectives included maximizing electrical energy regeneration and swing-phase reference joint biomechanics tracking [43]. Further information regarding such computational methods was not published. Gait experiments were conducted with able-bodied individuals wearing prosthetic emulator devices. The maximum energy regeneration efficiencies were approximately 30% [43]. To further increase electrical energy regeneration, the authors concluded that higher capacitance energy storage devices were needed but were commercially unavailable during that time [33].

### 4.2 Example 2: Semi-Powered Lower-Limb Prosthesis Design

Between 2007 and 2009, Andrysek's group designed and prototyped a regenerative braking semi-powered lower-limb prosthesis (see Fig. 3) [1, 8]. The design objectives included 1) achieve biomimetic swing-phase damping control using an electromagnetic machine, and 2) convert the otherwise dissipated mechanical energy into electrical energy for recharging the onboard batteries [1, 8]. The mechanical power transmission included spur gears and a planetary gearhead [8]. Electricity generation and mechanical damping were provided using a brushed DC electromagnetic machine [1, 8]. Wearable sensors (e.g., an accelerometer and rotary potentiometer) delivered feedback to the controller regarding the system operation [8]. MOSFET switches controlled the electrical energy between the electromagnetic machine and nickel-metal hydride batteries [1, 8]. The electrical circuit included a polarized capacitor [1, 8].

The prototype device weighed approximately 1.1 kg, resembling that of the semi-powered Össur Rheo Knee and Ottobock C-Leg [8]. Level-ground gait experiments were conducted with three (n=3) unilateral lower-limb amputee patients [8]. Throughout "comfortable" and "brisk" walking velocities, the prototype device generated approximately 2.1 W and 3.0 W of maximum electrical power, respectively. The corresponding average maximum energy regeneration efficiencies were 37% and 35% [8]. Reference joint biomechanics were obtained from the patient's contralateral biological lower-limbs using wearable sensors. The swing-phase damping controllers achieved prosthetic joint biomechanics that were approximately 90% comparable with the reference biomechanics [8].

**4.3 Example 3: Modelling and Optimal Control of Lower-Limb Prostheses**

Simon, Richter, Van Den Bogert, and colleagues have most recently investigated the design optimization and control of regenerative braking lower-limb prostheses through dynamic modelling and simulation [2, 9, 12, 35, 38, 47, 51, 57-59, 66-68, 80]. Their multibody system models included powered biomimetic hip joints with two degrees-of-freedom and semi-powered prosthetic knee joints with one degree-of-freedom [66]. The mechanical power transmissions comprised various combinations of ball-screw mechanisms, gears, and slider-crank linkages [2, 47, 59, 68]. The power conversion devices (i.e., DC electromagnetic machines) and energy storage devices (i.e., ultracapacitors) were computationally modelled using ideal gyrators and capacitors, respectively [2, 38, 47, 58, 66, 68, 80]. Different power modulating circuits like voltage source converters [2, 9, 38] and bidirectional buck-boost converters [9] were implemented to control the electrical energy between the simulated DC electromagnetic machines and ultracapacitors.

Biogeography-based evolutionary algorithms were employed to optimize various mechatronic design parameters (e.g., the mechanical power transmission geometry and capacitor electrical capacitance) [2, 12, 38, 47, 58-59, 66-68, 80]. The multiobjective optimizations included maximizing electrical energy regeneration and referencing joint biomechanics tracking [38, 47, 80]. Pareto efficiencies were used to analytically determine optimal weightings since the objective functions were conflicting (i.e., increasing electrical energy regeneration concurrently decreased the reference joint biomechanics tracking) [47, 66-67, 80]. Reference joint biomechanics were obtained from able-bodied individuals [38]. Tracking accuracies were quantified using root-mean-

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square deviations (RMSD). The optimizations produced "acceptable" amounts of maximum reference joint biomechanics tracking (RMSD of 1.0°) and energy regeneration (131 joules of electrical energy) throughout 5-second computer simulations, respectively [66]. The average maximum energy regeneration efficiencies were approximately 30% [38, 58, 68]. Moving forward, the authors suggested that incorporating human musculoskeletal dynamics and adaptive motor control representations into their computational models could facilitate more effective biomechatronic system optimizations [47].

**5. DISCUSSION**

Compared to conventional passive lower-limb prostheses and exoskeletons, the newly-developed biomechatronic devices have greater weights and limited operating durations [2, 4, 7-9, 11-12, 32, 50]. These shortcomings are particularly evident with powered assistive devices. For example, powered lower-limb prostheses under research and development have weighed between 1.7-6.9 kg (i.e., average of 4.0 ± 1.1 kg) and provided 1.5-8.7 hours of continuous functioning (i.e., average of 3.1 ± 2.2 hours) [4]. Most powered lower-limb exoskeletons have provided 1-5 hours of maximum operation [6]. Optimal power management control systems like regenerative braking could be utilized to minimize the onboard battery weight and/or extend the operating durations between recharging. This research reviewed the electromechanical design and optimization of lower-limb prostheses and exoskeletons with electrical energy regeneration. The technical review began with a biomechanical evaluation of human level-ground walking and proposed general design principles for regenerative braking prostheses and exoskeletons. The system design and optimization of different mechatronic components (i.e., the mechanical power transmission, electromagnetic machine, electrical drive, device mass and moment of inertia, and energy storage devices) were discussed. The technical review concluded by highlighting several examples of lower-limb biomechatronic devices with regenerative powertrains, the majority of which encompassed prosthetic knee mechanisms [1-2, 7-9, 12, 33-36, 38, 43, 47, 58-59, 66-68, 80]. Excluding the seminal research by Flowers's and colleagues during the 1980s [33-34, 36, 43], most research pertaining to lower-limb prostheses and exoskeletons with electrical energy regeneration have only recently been published (i.e., average publication year: 2014 $\pm$ 4).

**5.1 Current Limitations and Future Directions**

Despite the aforementioned technological advancements, there remains numerous innovative opportunities for maximizing electrical energy regeneration with lower-limb biomechatronic devices. The maximum amounts of regenerated electrical energy are fundamentally dependent upon 1) the system energy regeneration efficiencies, and 2) the maximum amounts of biomechanical energy available for regeneration [33, 36-37].

***5.1.1 Biomechanical Energetics***

Previous investigations of lower-limb prostheses and exoskeletons with regenerative powertrains have focused on level-ground walking [1-2, 8-9, 11-19, 33-34, 38, 43-44, 47, 58, 66, 68, 80]. Whereas the human knee joint biomechanics during level-ground walking encompasses high percentages of negative mechanical work, the

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amounts of mechanical energy available for regeneration are relatively limited (see Table 1). Dynamic movements like sitting down and slope and staircase descent alternatively necessitate significant amounts, and percentages, of negative mechanical work for braking control [3, 7, 11, 15, 44, 61-62, 66, 68, 81-82]. Grabowski and colleagues [81] recently demonstrated that patients with unilateral lower-limb amputations (n=10) walking at 1.25 m/s on level-ground performed approximately 0.25 J/kg of knee joint negative mechanical work during one locomotion stride. In comparison, walking down 9° slopes produced approximately 0.9 J/kg of knee joint negative mechanical work [81]. Steeper downward slopes theoretically require greater amounts of negative mechanical work for system deceleration, and therefore increased amounts of biomechanical energy available for regeneration [81]. Regenerating electrical energy during these everyday activities represents an unexplored and potentially effective method for recharging the onboard batteries of lower-limb prostheses and exoskeletons. Apart from biomechanical energy harvesting, quantitively investigating sitting and standing movements, and slope and staircase ambulation, would be clinically meaningful considering that minimal research has examined the biomechanics of geriatrics and rehabilitation patients performing these dynamic movements with lower-limb biomechatronic devices [3, 6-7, 61-62].

#### *5.1.2 Energy Regeneration Efficiencies*

Limited research has investigated the design optimization of lower-limb prostheses and exoskeletons conducive to maximizing energy regeneration efficiencies. Such optimizations would involve 1) systematically determining the mechanisms of

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energy dissipation and 2) minimizing such system inefficiencies. Building upon the legged robotics research from Kim's group [83-87], probable mechanisms of energy dissipation while ambulating with lower-limb biomechatronic devices include: Joule heating in the electromagnetic machine armature windings, friction in the mechanical power transmissions, and foot-ground inelastic impacts (see Fig. 4) [3, 10, 35-36, 48-50, 58-59, 67-68, 84-85]. Electrical battery self-discharging was considered relatively insignificant. Note that regenerative powertrain efficiencies depend upon both the actuator efficiency (i.e., mechanical-to-electrical energy conversion) and battery efficiency (i.e., electrical-to-chemical energy conversion). The energy dissipated from foot-ground inelastic impacts could be minimized by decreasing the impacting mass, specifically lighter mechatronic system designs [10, 46, 84-85, 87]. Joule heating has been the predominant mechanism of energy dissipation in many mechatronic locomotor systems, including lower-limb prostheses and dynamic legged robots [3, 10, 84-85]. Recent research involving regenerative braking lower-limb prostheses reported that energy dissipation from Joule heating was 2-3 times greater than that from friction in the mechanical power transmission [68].

Joule heating can be minimized using different mechatronic design configurations. Gear mechanisms with high transmission ratios theoretically decrease Joule heating by minimizing the electromagnetic machine torque requirements [10, 45-46, 84-85, 87-88]. Nevertheless, high-ratio mechanical power transmissions can increase the mechanism weight, friction, and mechanical impedance [10, 45-46, 48-49, 62, 85-88]. High mechanical impedances decrease the effectiveness of dynamic physical interactions with the surrounding environment (i.e., backdrivability) and increase the energy dissipation resulting from foot-ground inelastic impacts [10, 45-46, 48, 61, 83, 85-88]. Alternatively, employing electromagnetic machines with high-torque-densities can decrease Joule heating by minimizing the electrical current required for sufficient torque generation [45-46, 49, 84-85, 87-88]. High-torque-density electromagnetic machines can decrease the transmission ratios needed for dynamic locomotion, thereby circumventing the aforementioned deficiencies associated with high-gearing systems, while minimizing the energy dissipation resulting from Joule heating (see Fig. 4) [45-46, 88]. Implementing these mechatronic design principles, the dynamic legged robots from Kim's group have demonstrated maximum energy efficiencies above 63% [84-85]. In comparison, the maximum energy regeneration efficiencies of lower-limb biomechatronic devices have ranged between 30-37%. Future research should consider optimizing the mechatronic system designs of lower-limb prostheses and exoskeletons for maximizing energy regeneration efficiencies, thereby enabling geriatrics and rehabilitation patients to independently ambulate without the existing inconvenience of frequent recharging.

**6. CONCLUSION**

Electrical energy regeneration can enhance the energy efficiencies of lower-limb prostheses and exoskeletons via converting the otherwise dissipated biomechanical energy during human locomotion into electrical energy for recharging the onboard batteries, therein enabling lighter energy storage devices and/or extending the operating durations. This research reviewed the electromechanical design and optimization of regenerative powertrains for lower-limb biomechatronic devices. The technical review demonstrated that existing lower-limb prostheses and exoskeletons with electrical energy regeneration 1) are limited to level-ground walking applications, and 2) have maximum energy regeneration efficiencies between 30-37%. Accordingly, potential future directions for research and innovation include 1) regenerative braking during dynamic movements like sitting down and slope and staircase descent, and 2) utilizing high-torque-density electromagnetic machines and low-impedance mechanical power transmissions to maximize energy regeneration efficiencies.

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**REFERENCES**

[1] Andrysek, J., and Chau, G., 2007, "An Electromechanical Swing-Phase-Controlled Prosthetic Knee Joint for Conversion of Physiological Energy to Electrical Energy: Feasibility Study," IEEE Transactions on Biomedical Engineering, **54**(12), pp. 2276-2283. DOI: 10.1109/TBME.2007.908309.

[2] Rarick, R., Richter, H., Van Den Bogert, A., Simon, D., Warner, H., and Barto, T., 2014, "Optimal Design of a Transfemoral Prosthesis with Energy Storage and Regeneration," *Proceedings of the American Control Conference*, Portland, USA, June 4-6, 2014, pp. 4108-4113. DOI: 10.1109/ACC.2014.6859051.

[3] Lenzi, T., Cempini, M., Hargrove, L., and Kuiken, T., 2017, "Design, Development, and Testing of a Lightweight Hybrid Robotic Knee Prosthesis," The International Journal of Robotics Research, **37**(8), pp. 953-976. DOI: 10.1177/0278364918785993.

[4] Laschowski, B., and Andrysek, J., 2018, "Electromechanical Design of Robotic Transfemoral Prostheses," *Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Quebec City, Canada, August 26–29, 2018, pp. V05AT07A054. DOI: 10.1115/DETC2018-85234.

[5] Niu, P., Chapman, P., Riemer, R., and Zhang, X., 2004, "Evaluation of Motions and Actuation Methods for Biomechanical Energy Harvesting," *Proceedings of the IEEE Annual Power Electronics Specialists Conference*, Aachen, Germany, June 20-25, 2004, pp. 2100-2106. DOI: 10.1109/PESC.2004.1355442.

[6] Young, A. J., and Ferris, D. P., 2017, "State of the Art and Future Directions for Lower Limb Robotic Exoskeletons," IEEE Transactions on Neural Systems and Rehabilitation Engineering, **25**(2), pp. 171-182. DOI: 10.1109/TNSRE.2016.2521160.

[7] Tran, M., Gabert, L., Cempini, M., and Lenzi, T., 2019, "A Lightweight, Efficient Fully-Powered Knee Prosthesis with Actively Variable Transmission," IEEE Robotics and Automation Letters, **4**(2), pp. 1186-1193. DOI: 10.1109/LRA.2019.2892204.

[8] Andrysek, J., Liang, T., and Steinnagel, B., 2009, "Evaluation of a Prosthetic Swing-Phase Controller with Electrical Power Generation," IEEE Transactions on Neural Systems and Rehabilitation Engineering, **17**(4), pp. 390-396. DOI: 10.1109/TNSRE.2009.2023292.

[9] Barto, T., 2017, "Design and Control of Electronic Motor Drives for Regenerative Robotics," MS Thesis, Department of Electrical Engineering and Computer Science, Cleveland State University, USA.

[10] Kashiri, N., Abate, A., Abram, S. J., Albu-Schaffer, A., Clary, P. J., Daley, M., Faraji, S., Furnemont, R., Garabini, M., Geyer, H., Grabowski, A. M., Hurst, J., Malzahn, J., Mathijssen, G., Remy, D., Roozing, W., Shahbazi, M., Simha, S. N., Song, J. B., Smit-Anseeuw, N., Stramigioli, S., Vanderborght, B., Yesilevskiy, Y., and Tsagarakis, N., 2018, "An Overview on Principles for Energy Efficient Robot Locomotion," Frontiers in Robotics and AI, **5**(129). DOI: 10.3389/frobt.2018.00129.

[11] Tucker, M. R., and Fite, K. B., 2010, "Mechanical Damping with Electrical Regeneration for a Powered Transfemoral Prosthesis," *Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Montreal, Canada, July 6-9, 2010, pp. 13-18. DOI: 10.1109/AIM.2010.5695828.

[12] Warner, H., Simon, D., Mohammadi, H., and Richter, H., 2016, "Switched Robust Tracking/Impedance Control for an Active Transfemoral Prosthesis," *Proceedings of the American Control Conference*, Boston, USA, July 6-8, 2016, pp. 2187-2192. DOI: 10.1109/ACC.2016.7525242.

[13] Li, Q., Naing, V., and Donelan, J. M., 2009, "Development of a Biomechanical Energy Harvester," Journal of NeuroEngineering and Rehabilitation, **6**, pp. 22. DOI: 10.1186/1743-0003-6-22.

[14] Riemer, R., and Shapiro, A., 2011, "Biomechanical Energy Harvesting from Human Motion: Theory, State of the Art, Design Guidelines, and Future Directions," Journal of NeuroEngineering and Rehabilitation, **8**, pp. 22. DOI: 10.1186/1743-0003-8-22.

[15] Schertzer, E., and Riemer, R., 2015, "Harvesting Biomechanical Energy or Carrying Batteries? An Evaluation Method Based on a Comparison of Metabolic Power," Journal of NeuroEngineering and Rehabilitation, **12**, pp. 30. DOI: 10.1186/s12984-015-0023-7.

[16] Donelan, J. M., Naing, V., and Li, Q., 2009, "Biomechanical Energy Harvesting," *Proceedings of the IEEE Radio and Wireless Symposium*, San Diego, USA, January 18-22, 2009, pp. 1-4. DOI: 10.1109/RWS.2009.4957269.

[17] Selinger, J. C., and Donelan, J. M., 2016, "Myoelectric Control for Adaptable Biomechanical Energy Harvesting," IEEE Transactions on Neural Systems and Rehabilitation Engineering, **24**(3), pp. 364-373. DOI: 10.1109/TNSRE.2015.2510546.

[18] Donelan, J. M., Li, Q., Naing, V., Hoffer, J. A., Weber, D. J., and Kuo, A. D., 2008, "Biomechanical Energy Harvesting: Generating Electricity During Walking with Minimal User Effort," Science, **319**(5864), pp. 807-810. DOI: 10.1126/science.1149860.

Journal of Mechanisms and Robotics. Received June 01, 2018;
Accepted manuscript posted March 29, 2019. doi:10.1115/1.4043460



[19] Li, Q., Naing, V., Hoffer, J. A., Weber, D. J., Kuo, A. D., and Donelan, J. M., 2008, "Biomechanical Energy Harvesting: Apparatus and Method," *Proceedings of the IEEE International Conference on Robotics and Automation*, Pasadena, USA, May 19-23, 2008, pp. 3672-3677. DOI: 10.1109/ROBOT.2008.4543774.

[20] Hitt, J., Sugar, T., Holgate, M., Bellman, R., and Hollander, K., 2009, "Robotic Transtibial Prosthesis with Biomechanical Energy Regeneration," Industrial Robot: An International Journal, **36**, pp. 441-447. DOI: 10.1108/01439910910980169.

[21] Hitt, J. K., Sugar, T. G., Holgate, M., and Bellman, R., 2010, "An Active Foot-Ankle Prosthesis with Biomechanical Energy Regeneration," ASME Journal of Medical Devices, **4**(1), pp. 011003-011003-9. DOI: 10.1115/1.4001139.

[22] Mooney, L., and Herr, H., 2013, "Continuously-Variable Series-Elastic Actuator," *Proceedings of the IEEE International Conference on Rehabilitation Robotics*, Seattle, USA, June 24-26, 2013, pp. 1-6. DOI: 10.1109/ICORR.2013.6650402.

[23] Van Den Bogert, A. J., Samorezov, S., Davis, B. L., and Smith, W. A., 2012, "Modeling and Optimal Control of an Energy-Storing Prosthetic Knee," ASME Journal of Biomechanical Engineering, **134**(5), pp. 051007-051007-8. DOI: 10.1115/1.4006680.

[24] Alo, R., Bottiglione, F., and Mantriota, G., 2016, "Artificial Knee Joints Actuators with Energy Recovery Capabilities: A Comparison of Performance," Journal of Robotics, 2016, pp. 1-13. DOI: 10.1155/2016/4802474.

[25] Rome, L. C., Flynn, L., Goldman, E. M., and Yoo, T. D., 2005, "Generating Electricity While Walking with Loads," Science, **309**(5741), pp. 1725-1728. DOI: 10.1126/science.1111063.

[26] Rizzoni, G., and Peng, H., 2013, "Hybrid and Electrified Vehicles: The Role of Dynamics and Control," ASME Mechanical Engineering Magazine, **135**(03), pp. S10-S17. DOI: 10.1115/1.2013-MAR-5.

[27] Paradiso, J. A., and Starner, T., 2005, "Energy Scavenging for Mobile and Wireless Electronics," IEEE Pervasive Computing, **4**(1), pp. 18-27. DOI: 10.1109/MPRV.2005.9.

[28] Choi, Y. M., Lee, M. G., and Jeon, Y., 2017, "Wearable Biomechanical Energy Harvesting Technologies," Energies, **10**(10), pp. 1483. DOI: 10.3390/en10101483.

[29] Winter, D. A., 1983, "Energy Generation and Absorption at the Ankle and Knee During Fast, Natural, and Slow Cadences," Clinical Orthopaedics and Related Research, (175), pp. 147-154. DOI: 10.1097/00003086-198305000-00021.

Journal of Mechanisms and Robotics. Received June 01, 2018;
Accepted manuscript posted March 29, 2019. doi:10.1115/1.4043460



[30] Winter, D. A., 1991, The Biomechanics and Motor Control of Human Gait: Normal, Elderly, and Pathological, Waterloo Biomechanics, Waterloo, Canada.

[31] Rouse, E. J., Mooney, L. M., and Herr, H. M., 2014, “Clutchable Series-Elastic Actuator: Implications for Prosthetic Knee Design,” The International Journal of Robotics Research, **33**(13), pp. 1611-1625. DOI: 10.1177/0278364914545673.

[32] Sup, F., Varol, H. A., Mitchell, J., Withrow, T. J., and Goldfarb, M., 2009, “Preliminary Evaluations of a Self-Contained Anthropomorphic Transfemoral Prosthesis,” IEEE/ASME Transactions on Mechatronics, **14**(6), pp. 667-676. DOI: 10.1109/TMECH.2009.2032688.

[33] Seth, B., 1987, “Energy Regeneration and Its Application to Active Above-Knee Prostheses,” PhD Dissertation, Department of Mechanical Engineering, Massachusetts Institute of Technology, USA.

[34] Hunter, B, L., 1981, “Design of a Self-Contained, Active, Regenerative Computer Controlled Above-Knee Prosthesis,” MS Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, USA.

[35] Khalaf, P., and Richter, H., 2017, “On Global, Closed-Form Solutions to Parametric Optimization Problems for Robots with Energy Regeneration,” ASME Journal of Dynamic Systems, Measurement, and Control, **140**(3), pp. 031003-031003-12. DOI: 10.1115/1.4037653.

[36] Seth, B., and Flowers, W. C., 1990, “Generalized Actuator Concept for the Study of the Efficiency of Energetic Systems,” ASME Journal of Dynamic Systems, Measurement, and Control, **112**(2), pp. 233-238. DOI: 10.1115/1.2896130.

[37] Heinzmann, R. K., Seth, B., and Turi, J., 1992, “Application of a Generalized Actuator Model to the Study of Energy Regeneration Control Strategies,” ASME Journal of Dynamic Systems, Measurement, and Control, **114**(3), pp. 462-467. DOI: 10.1115/1.2897369.

[38] Barto, T., and Simon, D., 2017, “Neural Network Control of an Optimized Regenerative Motor Drive for a Lower-Limb Prosthesis,” *Proceedings of the American Control Conference*, Seattle, USA, May 24-26, 2017, pp. 5330-5335. DOI: 10.23919/ACC.2017.7963783.

[39] Seaman, A. N., and McPhee, J., 2010, “Symbolic Math-Based Battery Modeling for Electric Vehicle Simulation,” *Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Montreal, Canada, August 15-18, 2010, pp. 111-119. DOI: 10.1115/DETC2010-28814.

[40] Kim, S., Azad, N. L., and McPhee, J., 2015, "High-Fidelity Modelling of an Electric Vehicle," *Proceedings of the ASME Dynamic Systems and Control Conference*, Columbus, USA, October 28-30, 2015, pp. V002T34A006. DOI: 10.1115/DSCC2015-9743.

[41] Ing, A. H., and McPhee, J., 2015, "Automated Topology Optimization of Hybrid Electric Vehicle Powertrains," International Journal of Electric and Hybrid Vehicles, **7**(4), pp. 342-361. DOI: 10.1504/IJEHV.2015.074671.

[42] Au, S. K., Weber, J., and Herr, H., 2009, "Powered Ankle-Foot Prosthesis Improves Walking Metabolic Economy," IEEE Transactions on Robotics, **25**(1), pp. 51-66. DOI: 10.1109/TRO.2008.2008747.

[43] Tabor, K. A., 1988, "The Real-Time Digital Control of a Regenerative Above-Knee Prosthesis," MS Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, USA.

[44] Awad, M. I., Dehghani-Sanij, A. A., Moser, D., and Zahedi, S., 2016, "Motor Electrical Damping for Back-Drivable Prosthetic Knee," *Proceedings of the IEEE International Conference on Research and Education in Mechatronics and France-Japan and Europe-Asia Congress on Mechatronics*, Compiegne, France, June 15-17, 2016, pp. 348-353. DOI: 10.1109/MECATRONICS.2016.7547167.

[45] Zhu, H., Doan, J., Stence, C., Lv, G., Elery, T., and Gregg, R., 2017, "Design and Validation of a Torque Dense, Highly Backdrivable Powered Knee-Ankle Orthosis," *Proceedings of the IEEE International Conference on Robotics and Automation*, Singapore, May 29-June 3, 2017, pp. 504-510. DOI: 10.1109/ICRA.2017.7989063.

[46] Elery, T., Rezazadeh, S., Nesler, C., Doan, J., Zhu, H., and Gregg, R. D., 2018, "Design and Benchtop Validation of a Powered Knee-Ankle Prosthesis with High-Torque, Low-Impedance Actuators," *Proceedings of the IEEE International Conference on Robotics and Automation*, Brisbane, Australia, May 21-25, 2018, pp. 2788-2795. DOI: 10.1109/ICRA.2018.8461259.

[47] Rohani, F., Richter, H., and Van Den Bogert, A. J., 2017, "Optimal Design and Control of an Electromechanical Transfemoral Prosthesis with Energy Regeneration," PLoS ONE, **12**(11), pp. e0188266. DOI: 10.1371/journal.pone.0188266.

[48] Rezazadeh, S., and Hurst, J. W., 2014, "On the Optimal Selection of Motors and Transmissions for Electromechanical and Robotic Systems," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Chicago, USA, September 14-18, 2014, pp. 4605-4611. DOI: 10.1109/IROS.2014.6943215.

Journal of Mechanisms and Robotics. Received June 01, 2018;
Accepted manuscript posted March 29, 2019. doi:10.1115/1.4043460



[49] Lv, G., Zhu, H., and Gregg, R. D., 2018, "On the Design and Control of Highly Backdrivable Lower-Limb Exoskeletons: A Discussion of Past and Ongoing Work," IEEE Control Systems Magazine, **38**(6), pp 88-113. DOI: 10.1109/MCS.2018.2866605.

[50] Bolivar, E., Rezazadeh, S., and Gregg, R., 2017, "A General Framework for Minimizing Energy Consumption of Series Elastic Actuators with Regeneration," *Proceedings of the ASME Dynamic Systems and Control Conference*, Tysons, USA, October 11-13, 2017, pp. V001T36A005. DOI: 10.1115/DSCC2017-5373.

[51] Gualter Dos Santos, E., and Richter, H., 2018, "Modeling and Control of a Novel Variable-Stiffness Regenerative Actuator," *Proceedings of the ASME Dynamic Systems and Control Conference*, Atlanta, USA, September 30-October 3, 2018, pp. V002T24A003. DOI: 10.1115/DSCC2018-9054.

[52] Lawson, B. E., Shultz, A. H., and Goldfarb, M., 2013, "Evaluation of a Coordinated Control System for a Pair of Powered Transfemoral Prostheses," *Proceedings of the IEEE International Conference on Robotics and Automation*, Karlsruhe, Germany, May 6-10, 2013, pp. 3888-3893. DOI: 10.1109/ICRA.2013.6631124.

[53] Lawson, B. E., Mitchell, J., Truex, D., Shultz, A., Ledoux, E., and Goldfarb, M., 2014, "A Robotic Leg Prosthesis: Design, Control, and Implementation," IEEE Robotics & Automation Magazine, **21**(4), pp. 70-81. DOI: 10.1109/MRA.2014.2360303.

[54] Sup, F., Varol, H. A., Mitchell, J., Withrow, T. J., and Goldfarb, M., 2009, "Self-Contained Powered Knee and Ankle Prosthesis: Initial Evaluation on a Transfemoral Amputee," *Proceedings of the IEEE International Conference on Rehabilitation Robotics*, Kyoto, Japan, June 23-26, 2009, pp. 638-644. DOI: 10.1109/ICORR.2009.5209625.

[55] Martinez-Villalpando, E. C., and Herr, H., 2009, "Agonist-Antagonist Active Knee Prosthesis: A Preliminary Study in Level-Ground Walking," Journal of Rehabilitation Research and Development, **46**(3), pp. 361-373. DOI: 10.1682/JRRD.2008.09.0131.

[56] Martinez-Villalpando, E. C., Mooney, L., Elliott, G., and Herr, H., 2011, "Antagonistic Active Knee Prosthesis. A Metabolic Cost of Walking Comparison with a Variable-Damping Prosthetic Knee," *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Boston, USA, August 30-September 3, 2011, pp. 8519-8522. DOI: 10.1109/IEMBS.2011.6092102.

[57] Ghorbanpour, A., and Richter, H., 2018, "Control with Optimal Energy Regeneration in Robot Manipulators Driven by Brushless DC Motors," *Proceedings of the ASME Dynamic Systems and Control Conference*, Atlanta, USA, September 30–October 3, 2018, pp. V001T04A003. DOI: 10.1115/DSCC2018-8972.

[58] Warner, H. E., Simon, D., and Richter, H., 2016, "Design Optimization and Control of a Crank-Slider Actuator for a Lower-Limb Prosthesis with Energy Regeneration," *Proceedings of the IEEE International Conference on Advanced Intelligent Mechatronics*, Banff, Canada, July 12-15, 2016, pp. 1430-1435. DOI: 10.1109/AIM.2016.7576971.

[59] Richter, H., 2015, "A Framework for Control of Robots with Energy Regeneration," ASME Journal of Dynamic Systems, Measurement, and Control, **137**(9), pp. 091004-091004-11. DOI: 10.1115/1.4030391.

[60] Wildi, T., 2006, Electrical Machines, Drives and Power Systems, Pearson Education, USA.

[61] Shepherd, M. K., and Rouse, E. J., 2016, "Design and Characterization of a Torque-Controllable Actuator for Knee Assistance During Sit-to-Stand," *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Orlando, USA, August 16-20, 2016, pp. 2228-2231. DOI: 10.1109/EMBC.2016.7591172.

[62] Shepherd, M. K., and Rouse, E. J., 2017, "Design and Validation of a Torque-Controllable Knee Exoskeleton for Sit-to-Stand Assistance," IEEE/ASME Transactions on Mechatronics, **22**(4), pp. 1695-1704. DOI: 10.1109/TMECH.2017.2704521.

[63] Andrysek, J., Naumann, S., and Cleghorn, W. L., 2004, "Design Characteristics of Pediatric Prosthetic Knees," IEEE Transactions on Neural Systems and Rehabilitation Engineering, **12**(4), pp. 369-378. DOI: 10.1109/TNSRE.2004.838444.

[64] Andrysek, J., Naumann, S., and Cleghorn, W. L., 2005, "Design and Quantitative Evaluation of a Stance-Phase Controlled Prosthetic Knee Joint for Children," IEEE Transactions on Neural Systems and Rehabilitation Engineering, **13**(4), pp. 437-443. DOI: 10.1109/TNSRE.2005.856071.

[65] Maryniak, A., Laschowski, B., and Andrysek, A., 2018, "Technical Overview of Osseointegrated Transfemoral Prostheses: Orthopedic Surgery and Implant Design Centered," ASME Journal of Engineering and Science in Medical Diagnostics and Therapy, **1**(2), pp. 020801. DOI: 10.1115/1.4039105.

[66] Khademi, G., Mohammadi, H., Richter, H., and Simon, D., 2018, "Optimal Mixed Tracking/Impedance Control with Application to Transfemoral Prostheses with Energy Regeneration," IEEE Transactions on Biomedical Engineering, **65**(4), pp. 894-910. DOI: 10.1109/TBME.2017.2725740.

[67] Khalaf, P., and Richter, H., 2016, "Parametric Optimization of Stored Energy in Robots with Regenerative Drive Systems," *Proceedings of the IEEE International*

*Conference on Advanced Intelligent Mechatronics*, Banff, Canada, July 12-15, 2016, pp. 1424-1429. DOI: 10.1109/AIM.2016.7576970.

[68] Warner, H. E., 2015, "Optimal Design and Control of a Lower-Limb Prosthesis with Energy Regeneration," MS Thesis, Department of Mechanical Engineering, Cleveland State University, USA.

[69] Razavian, R., Azad, N. L., and McPhee, J., 2012, "On Real-Time Optimal Control of a Series Hybrid Electric Vehicle with an Ultra-Capacitor," *Proceedings of the American Control Conference*, Montreal, Canada, June 27-29, 2012, pp. 547-552. DOI: 10.1109/ACC.2012.6314831.

[70] Ekelem, A., Bastas, G., Durrough, C. M., and Goldfarb, M., 2018, "Variable Geometry Stair Ascent and Descent Controller for a Powered Lower Limb Exoskeleton," ASME Journal of Medical Devices, **12**(3), pp. 031009. DOI: 10.1115/1.4040699.

[71] Farris, R. J., Quintero, H. A., Withrow, T. J., and Goldfarb, M., 2009, "Design of a Joint-Coupled Orthosis for FES-Aided Gait," *Proceedings of the IEEE International Conference on Rehabilitation Robotics*, Kyoto, Japan, June 23-26, 2009, pp. 246-252. DOI: 10.1109/ICORR.2009.5209623.

[72] Farris, R. J., Quintero, H. A., Withrow, T. J., and Goldfarb, M., 2009, "Design and Simulation of a Joint-Coupled Orthosis for Regulating FES-Aided Gait," *Proceedings of the IEEE International Conference on Robotics and Automation*, Kobe, Japan, May 12-17, 2009, pp. 1916-1922. DOI: 10.1109/ROBOT.2009.5152634.

[73] Farris, R. J., and Goldfarb, M., 2011, "Design of a Multidisc Electromechanical Brake," IEEE/ASME Transactions on Mechatronics, **16**(6), pp. 985-993. DOI: 10.1109/TMECH.2010.2064332.

[74] Farris, R. J., Quintero, H. A., and Goldfarb, M., 2011, "Preliminary Evaluation of a Powered Lower Limb Orthosis to Aid Walking in Paraplegic Individuals," IEEE Transactions on Neural Systems and Rehabilitation Engineering, **19**(6), pp. 652-659. DOI: 10.1109/TNSRE.2011.2163083.

[75] Martinez, A., Lawson, B., and Goldfarb, M., 2018, "A Controller for Guiding Leg Movement During Overground Walking with a Lower Limb Exoskeleton," IEEE Transactions on Robotics, **34**(1), pp. 183-193. DOI: 10.1109/TRO.2017.2768035.

[76] Murray, S., and Goldfarb, M., 2012, "Towards the Use of a Lower Limb Exoskeleton for Locomotion Assistance in Individuals with Neuromuscular Locomotor Deficits," *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine*

*and Biology Society*, San Diego, USA, August 28-September 1, 2012, pp. 1912-1915. DOI: 10.1109/EMBC.2012.6346327.

[77] Murray, S. A., Ha, K. H., and Goldfarb, M., 2014, "An Assistive Controller for a Lower-Limb Exoskeleton for Rehabilitation after Stroke, and Preliminary Assessment Thereof," *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology*, Chicago, USA, August 26-30, 2014, pp. 4083-4086. DOI: 10.1109/EMBC.2014.6944521.

[78] Quintero, H. A., Farris, R. J., and Goldfarb, M., 2011, "Control and Implementation of a Powered Lower Limb Orthosis to Aid Walking in Paraplegic Individuals," *Proceedings of the IEEE International Conference on Rehabilitation Robotics*, Zurich, Switzerland, June 29-July 1, 2011, pp. 1-6. DOI: 10.1109/ICORR.2011.5975481.

[79] Quintero, H. A., Farris, R. J., and Goldfarb, M., 2012, "A Method for the Autonomous Control of Lower Limb Exoskeletons for Persons with Paraplegia," ASME Journal of Medical Devices, **6**(4), pp. 041003-041003-6. DOI: 10.1115/1.4007181.

[80] Khademi, G., Richter, H., and Simon, D., 2016, "Multi-Objective Optimization of Tracking/Impedance Control for a Prosthetic Leg with Energy Regeneration," *Proceedings of the IEEE Conference on Decision and Control*, Las Vegas, USA, December 12-14, 2016, pp. 5322-5327. DOI: 10.1109/CDC.2016.7799085.

[81] Jeffers, J. R., and Grabowski, A. M., 2017, "Individual Leg and Joint Work During Sloped Walking for People with a Transtibial Amputation Using Passive and Powered Prostheses," Frontiers in Robotics and AI, **4**, pp. 72. DOI: 10.3389/frobt.2017.00072.

[82] McFadyen, B. J., and Winter, D. A., 1988, "An Integrated Biomechanical Analysis of Normal Stair Ascent and Descent," Journal of Biomechanics, **21**(9), pp. 733-744. DOI: 10.1016/0021-9290(88)90282-5.

[83] Seok, S., Wang, A., Otten, D., and Kim, S., 2012, "Actuator Design for High Force Proprioceptive Control in Fast Legged Locomotion," *Proceedings of the IEEE International Conference on Intelligent Robots and Systems*, Vilamoura, Portugal, October 7-12, 2012, pp. 1970-1975. DOI: 10.1109/IROS.2012.6386252.

[84] Seok, S., Wang, A., Chuah, M. Y., Otten, D., Lang, J., and Kim, S., 2012, "Design Principles for Highly Efficient Quadrupeds and Implementation on the MIT Cheetah Robot," *Proceedings of the IEEE International Conference on Robotics and Automation*, Karlsruhe, Germany, May 6-10, 2013, pp. 3307-3312. DOI: 10.1109/ICRA.2013.6631038.

[85] Seok, S., Wang, A., Chuah, M. Y., Hyun, D. J., Lee, J., Otten, D. M., Lang, J. H., and Kim, S., 2015, "Design Principles for Energy-Efficient Legged Locomotion and

Implementation on the MIT Cheetah Robot," IEEE/ASME Transactions on Mechatronics, **20**(3), pp. 1117-1129. DOI: 10.1109/TMECH.2014.2339013.

[86] Wang, A., and Kim, S., 2015, "Directional Efficiency in Geared Transmissions: Characterization of Backdrivability Towards Improved Proprioceptive Control," *Proceedings of the IEEE International Conference on Robotics and Automation*, Seattle, USA, May 26-30, 2015, pp. 1055-1062. DOI: 10.1109/ICRA.2015.7139307.

[87] Wensing, P. M., Wang, A., Seok, S., Otten, D., Lang, J., and Kim, S., 2017, "Proprioceptive Actuator Design in the MIT Cheetah: Impact Mitigation and High-Bandwidth Physical Interaction for Dynamic Legged Robots," IEEE Transactions on Robotics, **33**(3), pp. 509-522. DOI. 10.1109/TRO.2016.2640183.

[88] Azocar, A. F., Mooney, L. M., Hargrove, L. J., and Rouse, E. J., 2018, "Design and Characterization of an Open-Source Robotic Leg Prosthesis," *Proceedings of the IEEE International Conference on Biomedical Robotics and Biomechatronics*, Enschede, Netherlands, August 26-29, 2018, pp. 111-118. DOI: 10.1109/BIOROB.2018.8488057.

**Table Caption List**

**Table 1** The resultant mechanical work, power, and torque about the ankle, knee, and hip joints during level-ground walking as determined from inverse dynamics simulations. Biomechanical data obtained from an 80-kg human walking at 1 m/s [5, 14, 30]. The negative work percentages (%) represent the intra-joint percentages of negative mechanical work from the total joint mechanical work performed during each step

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**Figure Captions List**

**Fig. 1** Schematic of the human knee joint biomechanics during level-ground walking. The resultant joint torque and rotational velocity are represented with tau and theta dot, respectively. Quadrants 1 and 2 occur during stance-phase, and quadrants 3 and 4 occur during swing-phase

**Fig. 2** Example of an electrical drive system for electromagnetic machines including both motoring and generating operations (i.e., represented with bidirectional arrows)

**Fig. 3** Photograph of the regenerative braking semi-powered lower-limb prosthesis designed and prototyped by Dr. Jan Andrysek (University of Toronto, Canada)

**Fig. 4** Representation of different energy dissipating mechanisms associated with mechatronic locomotor systems (i.e., lower-limb prostheses and exoskeletons, and dynamic legged robots), alongside recommended design principles for minimizing such system inefficiencies. Schematic adapted from Dr. Sangbae Kim (Massachusetts Institute of Technology, USA) [84-85]

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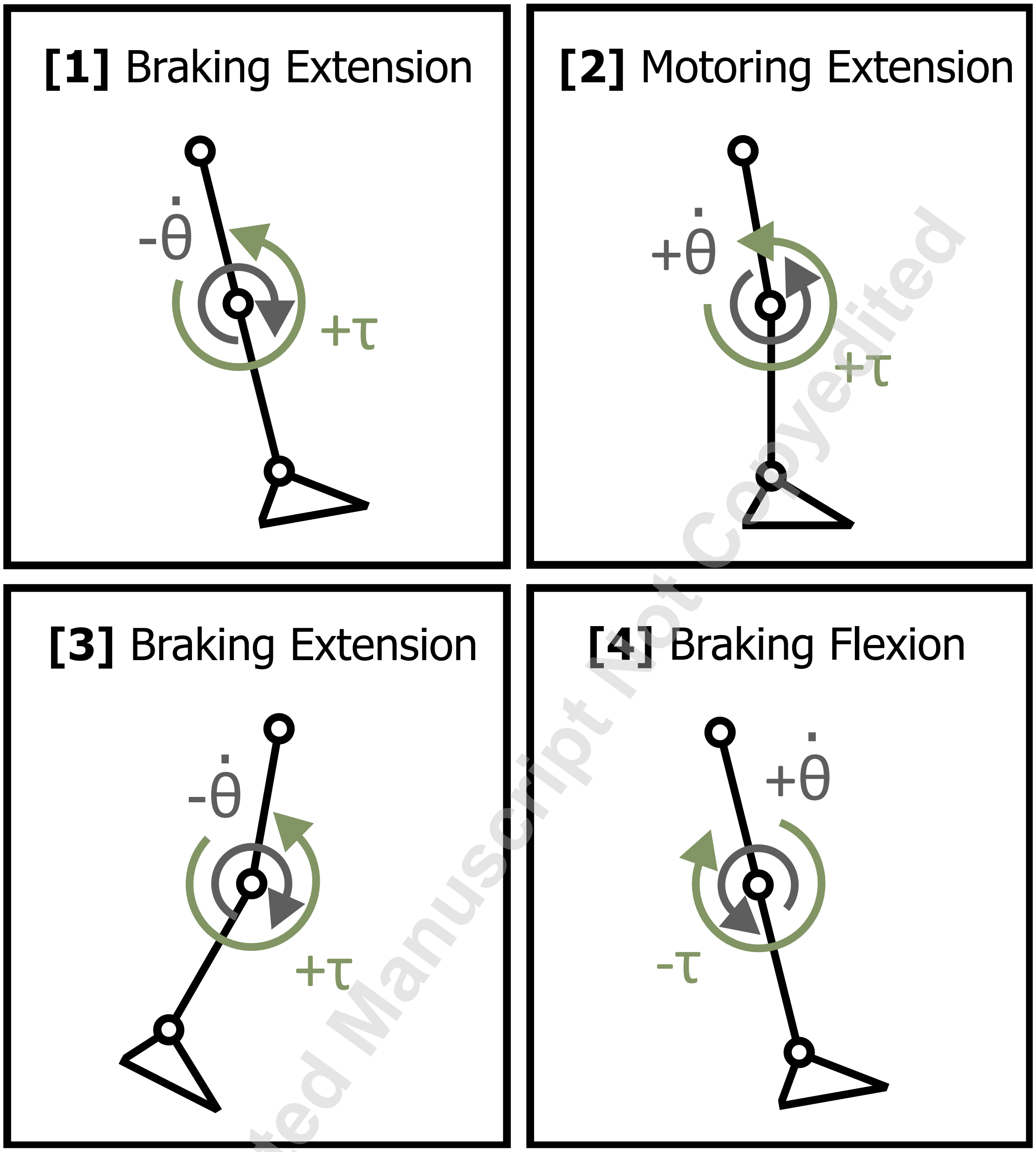
| Joint | Total Work (J/step) | Average Power (W) | Maximum Torque (Nm) | Negative Work (J/step) | Negative Work (%) |
|---|---|---|---|---|---|
| Ankle | 33.4 | 66.8 | 140 | 9.5 | 28.3 |
| Knee | 18.2 | 36.4 | 40 | 16.7 | 91.9 |
| Hip | 18.9 | 38 | 40-80 | 3.5 | 18.6 |

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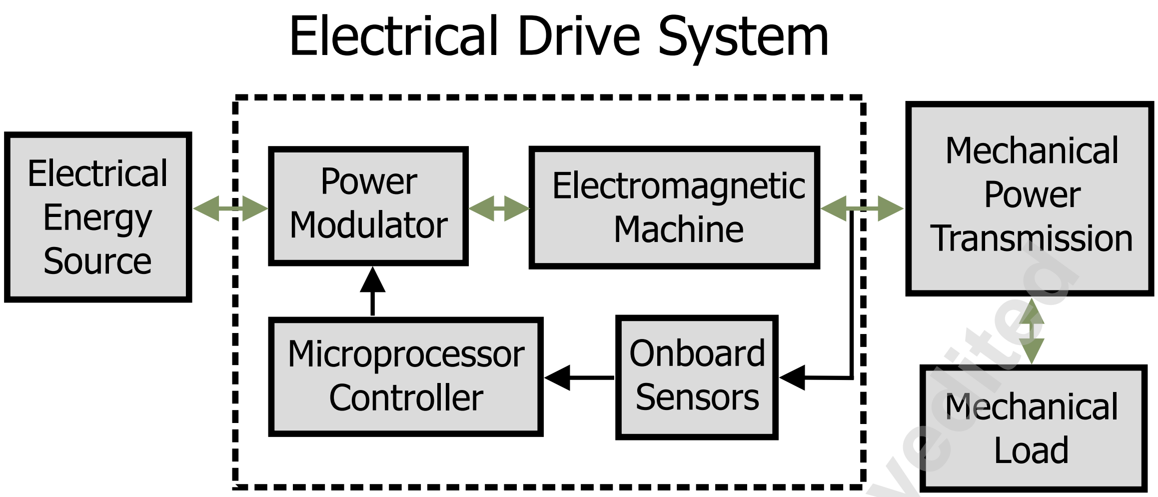


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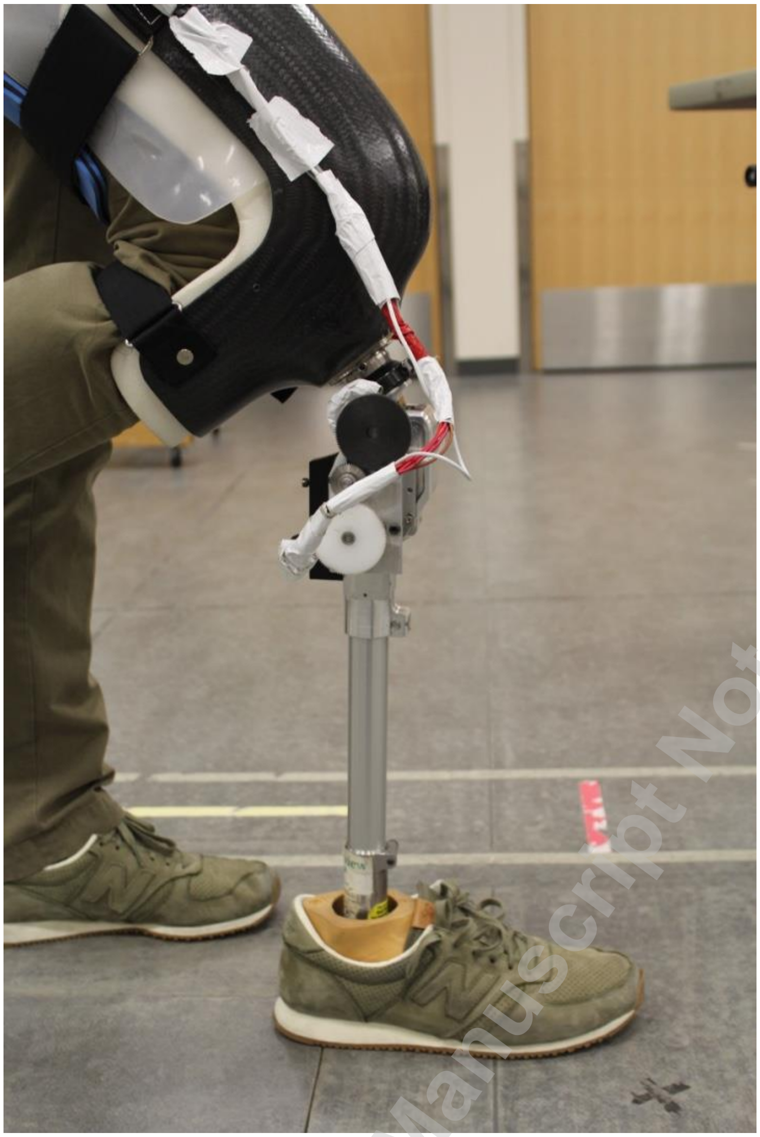

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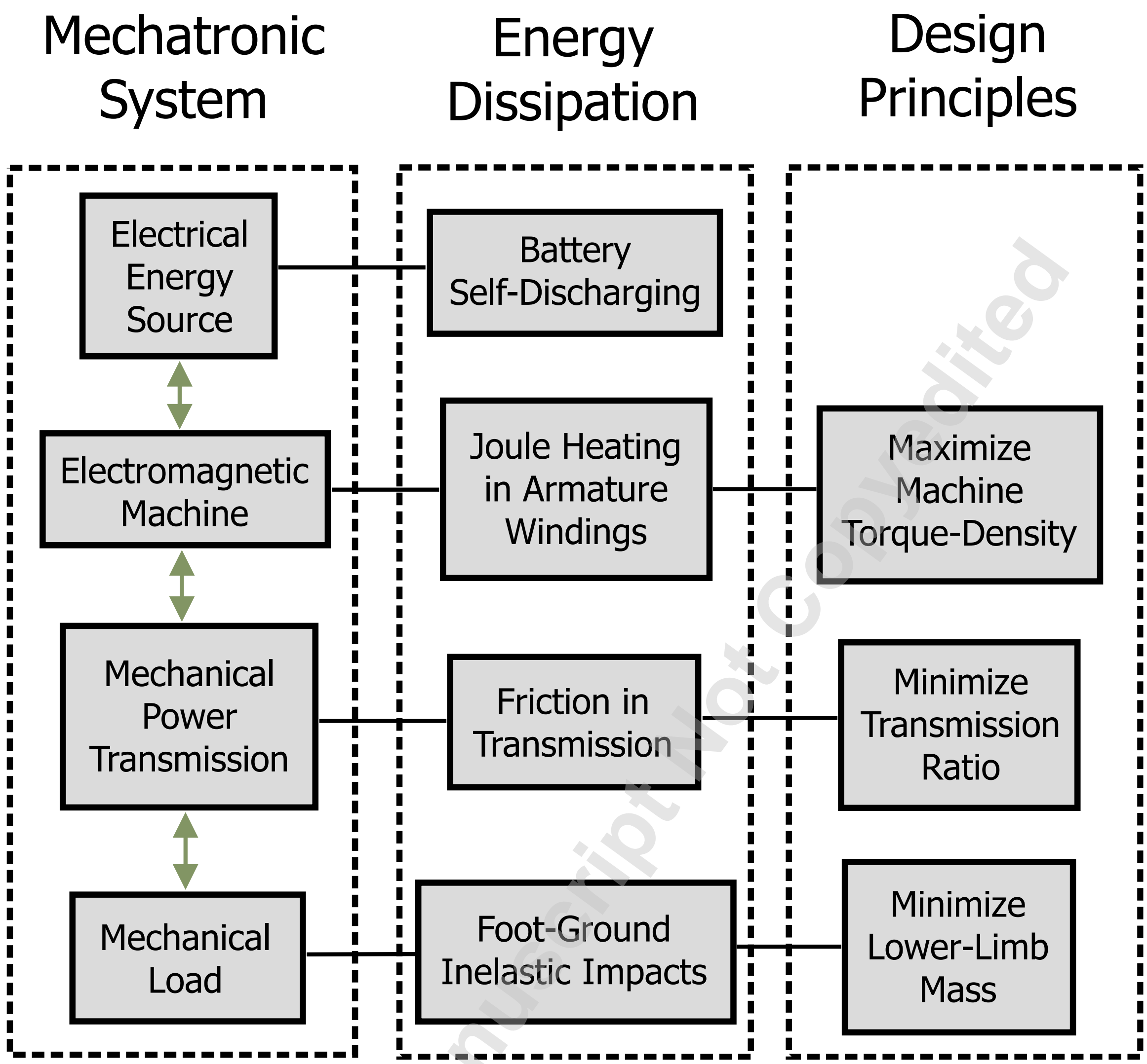


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