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Towards compliant and wearable robotic orthoses: A review of current and emerging actuator technologies

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ABSTRACT

Robotic orthoses, or exoskeletons, have the potential to provide effective rehabilitation while overcoming the availability and cost constraints of therapists. However, current orthosis actuation systems use components designed for industrial applications, not specifically for interacting with humans. This can limit orthoses' capabilities and, if their users' needs are not adequately considered, contribute to their abandonment.

Here, a user centered review is presented on: requirements for orthosis actuators; the electric, hydraulic, and pneumatic actuators currently used in orthoses and their advantages and limitations; the potential of new actuator technologies, including smart materials, to actuate orthoses; and the future of orthosis actuator research.

1. Introduction

Many people, including around 2% of adult New Zealanders, have a physical disability such as stroke, cerebral palsy, or a spinal cord injury and could benefit from rehabilitation [1–4]. However, effective rehabilitation requires long, intense, frequent, and task-based therapy sessions [5–7]. The cost and limited availability of therapists often prevent these requirements from being met to a satisfactory level [8]. The result is that people with physical disabilities do not receive optimal healthcare, limiting the quality of their everyday lives.

Robotic orthoses (hereon referred to as orthoses), have the potential to provide effective rehabilitation [9,10] of the upper [11] and lower limbs [12] while overcoming the limitations of therapists. They are computer controlled mechanical devices that are worn in parallel with the body and are designed to actively assist the user in moving their impaired limbs through a series of exercises representative of everyday tasks. Orthoses are moved by devices called actuators. Actuators convert a source of energy into mechanical motion. Traditionally, actuators have been based on electromagnetic motors and variable volume pressure chambers that use electricity, a pressurized liquid, or a pressurized gas to create movement. These are the electric, hydraulic, and pneumatic actuators predominantly used in current orthoses. New actuator technologies based on novel energy conversion mechanisms are also emerging. Some of these may have the potential to actuate future orthoses, when they have been furthered developed. An actuator cannot work on its own, but is part of an actuation system, which includes auxiliary components that provide and control its energy and hence motion. Current orthosis actuation systems use components such as motors, gearboxes, cylinders, pumps, valves, and compressors. These components are designed for industrial applications, not interacting with and being worn by humans. Often they result in heavy, rigid, and bulky actuators whereas an effective orthosis must, in general, be light, compliant, and portable [13,14]. This can reduce orthoses' functionality and some industrial actuator components may have a mechanical complexity that increases orthoses' cost [15,16]. Both these factors could contribute significantly to orthosis abandonment [17,18]. Hence, new actuator technologies need to be developed that are specifically designed to meet the needs of robotic orthoses and their users [19,20].

While significant progress has been made in advancing compliant actuation technologies for orthoses, more research is required to accompany the recent developments in soft sensor technologies [21], batteries, microelectronics, and composite materials that are making robotic orthoses a reality. For example, Vrije Universiteit Brussel's electric MACCEPA actuator features inherent compliance for safer and more efficient rehabilitation, yet uses readily available components for a low cost design [22]. Harvard's soft glove hydraulic actuation [23] and high-speed electric winch driven lower limb exosuit focus on joint assistance in a comfortable and non-restrictive manner [24]. Despite orthosis actuator advances, current actuation solutions make compromises between performance and wearability to the detriment of orthoses that meet their users' needs.

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Table 1
Summary of orthoses reviewed categorized by orthosis type and actuator technology.

Orthosis type	Actuator technology (number of orthoses)	Citations
Upper limb	Electric (11)	[15,26,28–36]
	Hydraulic (3)	[23,37,38]
	Pneumatic (6)	[39–47]
Lower limb	Electric (16)	[22,24,48–62]
	Hydraulic (2)	[63,64]
	Pneumatic (1)	[65]
Full body	Electric (1)	[66]
	Hydraulic (0)	–
	Pneumatic (2)	[67,68]

This paper begins with a systematic review of essential actuator requirements common to all robotic orthoses and taken from the perspective of orthosis stakeholders' needs. These requirements are used to critically evaluate current and potential orthosis actuator technologies. Finally, a discussion is given on potential research directions that the limitations of these technologies provide for developing successful actuators for future orthoses. Actuator requirements for a particular orthosis application are outside of the scope of this review. Readers interested in designing orthosis actuation systems for their specific rehabilitation application are referred to the orthoses reviewed for their use of current actuators (Table 1). For joint torque and motion requirements, the reader is referred to orthosis design papers, such as Rosen et al. and Perry et al. on upper limb orthoses [25,26] and Zoss et al. on lower limb orthoses [27].

2. Orthosis actuator requirements

In the past, high proportions of mechanical orthoses have been abandoned by their users [17,69]. To help prevent this from occurring with robotic orthoses, the requirements that describe the characteristics of orthosis actuators should capture the needs of orthoses' key stakeholders. These stakeholders are the user, their family members, clinicians, and health care providers [17,70]. If an actuator is to be developed for a user acceptable orthosis, the stakeholders must also be integral to the entire development process by providing feedback during experiments and clinical tests. This feedback can then be used to validate that fulfillment of the actuator requirements contributes to meeting the stakeholders' needs [71,72].

Here, Table 2 summarizes these stakeholder needs and how they are related to a selection of essential actuator performance, physical, and safety requirements. The stakeholder needs were taken as nine of the "necessary and sufficient" needs originally proposed by Batavia and Hammer [73], and later refined by Lane et al. [74], that were most relevant to orthosis actuation. We then conducted an extensive literature review to determine the actuator requirements important to meeting those needs. It was found that important performance requirements are compliance [37,43,68]; high specific power [38,42] and force [35,45]; natural motion characteristics [33,36,63,64]; infinitely variable backdrivability [15,48,64,75]; ease of control [15,26,39,58]; and efficiency [63]. Key physical requirements include low mass [47], slim form [23,29,48,61,63], low cost [14,40], modularity [15,22,33,47], environmental compatibility [28,68], and quietness [40]. Lastly, significant safety requirements are sanitary cleanliness [68]; safe exposed parts [33,38,46,52]; and limited range of motion (ROM), speed, and force [43]. The actuator requirements were derived from robotic orthosis researchers' opinions on desirable and undesirable orthosis features relevant to their actuation. They are general and suggested as a starting point for more specific requirements for a given orthosis application.

Most of the stakeholder needs and some of the actuator requirements are self-explanatory; however, a few need extra comment. Orthosis portability is important for home-based rehabilitation devices. Such devices offer the benefits of more effective recovery of functional independence through rehabilitation strategies based on the user's activities of daily living in a home environment [13]; and increased accessibility to treatment leading to greater rehabilitation effectiveness and lower costs [7,76].

Table 2
Orthosis stakeholder needs and examples of how they relate to selected actuation requirements.

Stakeholder need	Definition [73,74]	Requirement example	Citation
Affordability	The financial burden of the initial purchase and ongoing orthosis costs	Physical: low cost – the Hand Mentor uses a low cost pneumatic muscle actuator (PMA) to reduce the capital cost of the orthosis, improving its affordability.	[40]
Durability	The expected useful lifetime of the orthosis	Physical: environmental compatibility – the Myomo mPower packages its actuator components against the ingress of water and dirt, allowing the orthosis to survive the wear of everyday indoor environments for a long time.	[28]
Easy to maintain/repair	The ease of keeping the orthosis fully operational, including when damaged	Physical: modular – the RehabExos has modular actuation units, making it easier to assemble and replace them during maintenance.	[15]
Effectiveness	The ability of the orthosis to improve the user's quality of life	Performance: natural motion characteristics – the IntelliArm actuators have the range of motion a human uses for everyday tasks. This enables it to engage the user in effective task-based passive stretching exercises representative of normal activities.	[36]
Operability	The device is easy to control and adaptable to changes in the user's size and disability level	Performance: infinitely variable backdrivability – ALEX uses software to make its actuators backdrivable so they do not resist the user's intentions. This makes it easier to control and use.	[75]
Physical: comfort/acceptance	The fit, appearance, and sound of the orthosis does not cause the user to feel pain or stigmatized	Physical: slim form – the modular and inline arrangement of the Indego orthosis' actuators minimizes its profile to make it less noticeable.	[61]
Portability	The ability of the orthosis to be transported between locations	Physical: low mass – the OrthoJacket uses lightweight pneumatic actuators to enable it to be a completely portable system that can be part of everyday life.	[47]
Reliability	The consistency of the orthosis' operation in normal operating conditions	Performance: ease of control – CADEN-7's actuators are designed for natural and stable control so the orthosis can be relied on to behave predictably.	[26]
Safety	The potential for the orthosis to harm its user (or others)	Safety: limited ROM, speed, and force – RUPERT's safety is maximized by the inherently limited stroke of its PMA actuators combined with the PMAs' speed and force limits imposed by air supply flow and pressure restrictions.	[43]

Table 3
A comparison of the specific force, power, and efficiency of human muscle with that of actuator technologies currently used in orthoses.

Actuator type	Electric		Hydraulic		Pneumatic		Biological
	Rotary motor with ballscrew transmission	Water-cooled direct drive linear motor	Electrohydraulic actuator	Portable double acting cylinder system	Double acting cylinder	Antagonistic PMA pair	Human skeletal muscle
Citations	[87,88]	[89,90]	[91]	[63,92–94]	[95–98]	[95,96,98,99]	[99–102]
Specific force (N/kg)	1210	140	680	660	20	120	1000
Specific power (W/kg)	140	100	50	90	40	40	50
Efficiency (%)	80	40	40	7	<30		30

Among the performance requirements, high specific power and force infers that an orthosis' actuator and its auxiliary components must provide similar levels of power [41] and force [43] to the human muscles it is emulating in an unobtrusive and low mass form. Hence, the specific power and force of human skeletal muscles can be taken as a performance benchmark (see Table 3). This benchmark will be raised for heavier users or users with higher muscle spasticity to overcome their additional joint inertia or passive joint stiffness [43]. However, orthoses that provide partial assistance and thereby promote user involvement (for example [22]) will have a lower benchmark. Additionally, the calculation of these metrics should consider the mass of auxiliary components to ensure the wearability of autonomous orthoses and portability of mains powered orthoses. These components include transmission elements, valves, pumps, or power electronics, depending on the actuator technology. The actuators' energy source mass should also be included if information on the actuators' average power consumption and desired operation time (usually eight hours of intermittent use) is available. The natural motion characteristics requirement refers to the desired smoothness [64], speed, acceleration [33], and ROM [36,63] of actuator motion, which matches that of a human doing everyday tasks. Where feasible, actuator compliance should be inherent [68] and variable [14]. Inherent compliance is more robust, safer, and uses less power than software rendered compliance [77,78]. Variable compliance is needed so that the orthosis can accurately match the task dependent compliance of a human [14,43], where increasing compliance is required for tasks that have reduced bandwidth, force, and accuracy [54]. The infinitely variable backdrivability requirement means that when the orthosis is in an assistive mode, the actuator must not resist the orthosis user's voluntary movements [75]. However, it must also have limited [15] or no backdrivability during an emergency such as a power loss to prevent its user from collapsing [64].

The physical requirement of lightweight actuators ensures user comfort. Both the magnitude and placement of an orthosis actuator's mass should have a minimal increase in the inertia of its user's limbs and be primarily distributed around the user's torso [79]. As a guideline, for the orthosis to be comfortably worn all day, its total unsupported or unpowered mass (of which the actuator is only one part) located on the torso, each foot, or in each hand needs to be less than 15%, 1.25%, or 3.75% of the user's body weight respectively [80,81]. A slim actuator form is essential for an orthosis that does not impede its user's motion [61] and is able to be integrated with [47] or hidden under one's clothing. Users appreciate the unobtrusiveness of a slim form-fitting orthosis [48,82,83]. Taking passive orthosis dimensions as a reference for an acceptably slim device [84], the actuator thickness should be less than 30 mm and ideally less than 10 mm thick when located on distal segments of limbs. Given that some of the actuator parts can be positioned on the orthosis user's back, and the user is an adult male, this allows a total volume of 3–10 l for an upper limb orthosis and 5–23 l for a lower limb orthosis [85]. The lower volume limits are for unilateral limb orthoses with a 10 mm uniform thickness and the upper limits for bilateral orthoses with a 30 mm uniform thickness. Fundamental to an actuator's durability is its environmental compatibility. This means that the actuator has appropriate dust and moisture protection to reflect the environment it is designed for, whether indoors or outdoors [86].

The safety requirement that actuators have a limited ROM, speed, and force [43] ensures that harmful angular displacements, angular velocities, or torques are not applied to a joint. This can best be achieved through inherent actuator properties like compliance and mechanical limit stops. However, even an inherently compliant actuator is capable of producing assistive forces that could harm a person if applied incorrectly. Hence, although it is outside the scope of this paper, a robust and effective actuator controller is also essential to the safety of orthosis actuators.

3. Current orthosis actuator technologies

A review was conducted on the actuator technologies used in orthoses with the Scopus, Google Scholar, Web of Science, and ProQuest Dissertations and Theses databases. To ensure comprehensive coverage of the literature, we used the generic search term (and its database specific equivalents) “actuat* AND (exoskeleton* OR rehabilitat* OR orthotic* OR orthos* OR therap* OR prosthe* OR (human* and interaction*))” to retrieve over 10,000 results. The final subset of orthosis actuation literature reviewed in this section (summarized in Table 1) is the outcome of restricting results to those orthoses that have had ongoing development within the last decade and had good critique on, and justification for the actuator technology used. The review revealed that upper, lower, and full body orthoses mainly used one of the three traditional actuator technologies: electric motors, hydraulics, or pneumatics.

3.1. State-of-the-art

A number of orthoses are available commercially and these are either electrically or pneumatically actuated. Lower limb orthoses include the Rex (Rex Bionics Ltd., Auckland, New Zealand) with five actuated degrees-of-freedom (dof) per leg and the Ekso (Ekso Bionics Holdings, Inc., Richmond, CA), Indego (Parker Hannifin Corp., Cleveland, OH), ReWalk (ReWalk Robotics, Inc., Marlborough, MA), HAL (Cyberdyne Inc., Tsukuba, Japan), Keeogo (B-Temia Inc., Québec, Canada), ARKE (Bionik Laboratories Corp., Toronto, Canada), and Lokomat (Hocoma AG, Volketswill, Switzerland), all with two actuated dof per leg. With the exception of the Lokomat, which is treadmill mounted, all of these orthoses are completely autonomous and battery powered. They are actuated by electric servomotors, typically consisting of an electric motor and transmission elements such as harmonic drives, ballscrews, timing belts, or sprockets and chains. The commercially available upper limb ArmeoPower (Hocoma AG, Volketswill, Switzerland) and MyoPro (Myomo Inc., Cambridge, MA) orthoses are also actuated by electric servomotors. The ArmeoPower is ground mounted and has six actuated dof across the shoulder, elbow, and wrist joints, while the MyoPro is a battery powered orthosis with one actuated dof at the elbow. To our knowledge, Kinetic Muscles Inc.'s Hand

Mentor (Kinetic Muscles Inc., Tempe, AZ) is the only commercially available pneumatically actuated orthosis. It has a single dof at the wrist driven by a pneumatic muscle actuator (PMA). The PMA is pressurized by a desk mounted air compressor. Unlike commercial exoskeletons for strength augmentation, such as Lockheed Martin's HULC, hydraulic actuators have not yet been used in commercial orthoses.

Current orthosis actuator technologies have complementary characteristics that collectively capture the essential actuator requirements. However, when considered separately, each technology has significant shortcomings that are highlighted when assessing the auxiliary components and actuator together as a potentially independent and wearable system.

Six variations of traditional actuators are compared in Table 3 with the orthosis performance requirements that are easily quantified: specific power, specific force, and efficiency. Data for the performance of human skeletal muscle is also given for reference. The results shown are representative figures, rather than absolute performance limits, that approximate the performance of commercial and prototype actuators a similar size to those used in orthoses. The specific power and force were taken as the ratio of the continuous power or force a given actuator produced to the mass of it and its auxiliary components, but excluding the energy source. Actuator efficiencies are given for the actuators producing their rated continuous power output.

Of the actuators in Table 3, the electrohydraulic actuator integrates an electric motor, gear pump, and double acting cylinder into one unit. The portable double acting hydraulic cylinder is controlled by servo valves and powered by a gear pump and internal combustion engine. The pneumatic actuators are both powered by an air compressor via solenoid valves. The comparison highlights that when the mass of auxiliary components is considered, the specific power and force of the electric motor with transmission and hydraulic actuators are comparable to that of human muscle. Importantly, this verifies that the specific power and force of completely portable traditional actuator systems on an orthosis scale are appropriate for orthosis actuation. The lower specific force of direct drive electric and pneumatic actuators make them more suitable for orthoses that transfer some of their weight to the ground. Examples of these are treadmill based lower limb [52] and desk or wheelchair mounted upper limb orthoses [40].

On a qualitative level, the advantages of each traditional actuator technology are clear. For example, an electromagnetic prime mover is easily controllable, battery powered (making it portable), and efficient. A hydraulic transmission is silent, precise, and smooth; supports high specific power and force; is impervious to dusty and wet environments; has no exposed moving components; and with valves can have infinitely variable backdrivability. Antagonistically actuated pairs of pneumatic muscle actuators (PMA) have inherently variable compliance; a high force output; and a limited ROM, speed, and force. Current actuators can cumulatively meet the requirements of orthoses, but individually have serious limitations that make orthoses bulky, rigid, and impractical as wearable devices.

Table 4
Core actuator technology selection reasons.

Actuator technology	Selection reason	Citation
Electric motors	High specific power	[29]
	Easy to control	[58]
Hydraulic cylinders	Compact	
	High specific power	[38,63]
	High force output	
	Wide control bandwidth	
	Low mass	
	Compact	
	Smooth actuation	[64]
	Fast response to a change in input	
	Actuator can be remotely located	
	Force output and speed scales with actuator dimensions or operating pressure	
Pneumatic cylinders and PMA	High specific power	[68]
	High specific force	
	Inherent compliance	
	Low mass	
	Low cost	
	Hygienic	
	Flexibility and softness of biological muscle (PMA)	
	Elastic load-displacement characteristics	[40]
	Low profile	
	Quiet	
	No energy required to generate a blocking force	[41]
	Compliance similar to human joint	[44]
	Reduced control bandwidth due to compliance	
	Backdrivable	[46]
	Easily integrated with orthosis and user's clothing	[47]
	Variable compliance through antagonistic actuation	[68]
	Robust to wet and dirty environments	
	Force output scales with actuator dimensions or operating pressure	[43]

3.2. Limitations

Alongside the advantages of current orthosis actuators are a number of fundamental limitations that prevent their successful application in compliant and wearable orthoses.

Electric actuators' are limited by their need for transmission elements to convert their high-speed, low-torque output to the low speeds and high torques needed to drive orthoses [78,103]. These transmission elements may negatively affect the backdrivability [36,75,104], efficiency, safety, size [37,48], mass [105], noise [50], cost [48], and complexity of electric actuators. Battery technology does not necessarily limit electric orthoses' portability and operation times [10,48]. The doubling of commercial battery energy density in the last two decades [106] and commercially available untethered orthoses [107,108] show that batteries can be a viable orthosis energy source if they are used with efficient actuators.

A significant limitation of hydraulic and pneumatic actuators is their dependence on non-portable pressure supplies. The prime movers and pumps or air compressors that currently pressurize fluids (both air and liquids) are too heavy and large [109,110], reducing the achievable specific power of these actuators far below what it could potentially be. As a result, these technologies have been limited to tethered orthoses with no or low portability. Another fundamental limitation of hydraulic and pneumatic actuators is their inefficiency (Table 3). This is mainly due to the large amounts of power lost in pressure drops across hydraulic and pneumatic valves [111]. The efficiency of pneumatics is also worsened by the difficulty in efficiently compressing air, as it is inherently compliant [112].

In aid of overcoming the aforementioned limitations, it is useful for orthosis researchers to discuss the capabilities and limitations of applying their chosen actuator technologies specifically to orthoses. This enables future orthosis actuator researchers to learn from others' experiences and helps them to actively develop the actuator technologies with the limitations most readily overcome with current technology. By way of example, Table 4 summarizes the primary selection reasons documented by researchers of the orthoses in this review.

4. Future orthosis actuator technologies

In recent years, a lot of research has been devoted to developing completely new actuator technologies that may eventually be viable alternatives to the traditional actuators used in current orthoses. The following section will examine the actuation mechanisms and fundamental limitations of promising rigid and soft smart materials, electrostatic actuators, and chemically powered actuators.

4.1. New actuation mechanisms

Two promising rigid smart materials are shape memory actuators (SMAs) and carbon nanotube (CNT) actuators. Both actively cooled SMAs [113] and CNT actuators [114-116] can produce high force with a speed and specific power similar to human muscle. SMAs have already been applied to upper [83] and lower limb [117] orthoses. An SMA is made of shape memory alloy wires pre-tensioned against a bias load. This pre-tensioning permanently deforms the microscopic structure of the SMA's wires. The wires contract when heating reversibly transforms their microscopic structure to its undeformed state [118]. This is done by passing an electric current through the SMA or with the exothermic reaction of a fuel, oxidizer, and catalyst [119]. A bending CNT actuator is made by bonding a single walled carbon nanotube electrode to either side of a thin insulating material and immersing it in an electrolyte. Applying a voltage to the electrodes draws ions in the electrolyte to the electrodes' surface. This triggers quantum chemical and electrostatic effects that increase the covalent bond lengths between carbon atoms in the electrodes, causing them to expand. Due to the different potentials of the electrodes, one expands more than the other and the actuator bends [120].

Dielectric elastomer actuators (DEAs) are a soft smart material made of an insulating elastomer layer sandwiched between thin compliant electrodes. They are promising for orthosis actuation because they have a stress, strain, speed, and specific power similar to human muscle [115,121,122], and like muscle, are capable of self-sensing their position [123]. A DEA actuates when an electric field applied across its electrodes generates an electrostatic force that compresses the elastomer in the thickness direction. This simultaneously causes it to expand outwards in a plane perpendicular to the electric field, translating the load it is coupled to [124]. Carpi et al. have used this principle to actuate a hand splint orthosis in [125].

Another soft smart material is the polymeric molecular actuator. This actuator is made of molecules designed so that electromagnetic, chemical, or electrical energy modifies their bonds in a way that alters the molecules' shape. The coordinated actuation of many of these molecules changes the shape of the material they make up. An example of a polymer actuator molecule is poly(CalixBBT). It has hinged bonds that fold up when it is oxidized, resulting in contraction of the bulk polymer [115,126]. Polymeric molecular actuators are a potential future orthosis actuator because their stress and strain is similar to human muscle with the possibility to be scaled to a size that produces useful amounts of work [115,126–128].

The electro-conjugated fluid actuator is a novel electrostatic actuator that uses an electrostatic pump to pressurize a dielectric fluid and expand a bellows or PMA style mesh constrained bladder [129]. In the pump, high voltage is applied to a pair of electrodes designed to generate a non-uniform electric field in a dielectric fluid [130]. This creates Maxwell pressure gradients that impart kinetic energy to the fluid, making it flow [131]. Future orthoses could use this technology as it has a specific power output twice that of human muscle [130,132], and is quiet and reliable with no moving parts [133].

Table 5
Fundamental limitations of promising orthosis actuator technologies.

Actuator type	Fundamental limitations
Shape memory	Low efficiency [118] Low strain [115]
Carbon nanotube	Very low efficiency [114,115] Too thin to produce useful amounts of power and force [140]
Dielectric elastomer	Manufacturing processes are currently unable to produce a reliable actuator of a size that can produce useful amounts of power and force [141] The size and mass of their supporting structures and mechanisms [124,142]
Polymeric molecular	Actuation of individual molecules must be coordinated for good performance of the bulk actuator [115] Very low efficiency [127]
Electro-conjugated fluid	Specific power of actuator decreases with size, making it uncompetitive with electromagnetic actuators when scaled to a size that produces useful amounts of power and force [130,132] Low efficiency [132]
Monopropellant	Monopropellants are dangerous and highly reactive substances [134,135] Low efficiency [135]
Engineered muscle tissue	Requires a regulated environment to function [136] Difficult to couple actuator tissue to a mechanical load [136]

Chemically fuelled actuators take advantage of the high energy density of chemicals. The monopropellant chemical actuator meters a chemical monopropellant through a mesh catalyst into a reaction chamber. The catalyst causes the monopropellant to undergo an exothermic decomposition reaction, producing high pressure and high temperature gases that expand a bellows or extend a piston against its load [134,135]. This actuation principle produces the high specific power and force required of orthosis actuators [134,135]. Engineered muscle tissue actuators are made from specially grown muscle tissue, that when appropriately encapsulated can use the same actuation principle as human muscle to convert chemical energy into mechanical energy [136]. With the potential to exactly copy and perhaps exceed the capabilities of natural skeletal muscle [136] these are promising orthosis actuators. As in human muscle, millions of protein actuation units called sarcomeres make up engineered muscle tissue actuators. When they are activated by electrical impulses, the hydrolysis of the chemical Adenosine Triphosphate (ATP) is permitted, causing protein filaments in each sarcomere to ratchet along each other. This makes the sarcomeres and hence muscle contract for as long as the activating electrical impulses are present [137-139].

4.2. Fundamental limitations

Table 5 summarizes two of the current fundamental limitations for each of the new actuator technologies examined in this review. Most have the limitation of low actuation efficiency, making them incompatible with the relatively low energy densities of current batteries and hence non-portable. Other actuators, particularly smart materials and electrostatic actuators, cannot be manufactured in a size large enough to generate the power and force levels required for an orthosis actuator. A recurring limitation is the negative impact that the mass of auxiliary components such as frames and strain amplification mechanisms have on their specific power and force.

The DEA is a particularly promising actuator. Unlike the other new actuator technologies, DEAs do not suffer from limitations relating to strain, speed, power, force, stiffness, encapsulation, and efficiency. In common with other new actuators, they have advantages over traditional actuation in being silent, solid-state, and soft.

However, their application to orthosis actuation is currently limited by their high voltage; bulky and expensive electronics; and the difficulty in manufacturing DEAs of a size that are capable of reliably producing useful amounts of power and force. This shows that at present, despite the intense research on new actuators, even the most promising of these technologies requires several substantial advances to be made before it can be considered as an alternative to the traditional orthosis actuators.

5. Future research trends

Given the limitations of current orthosis actuator design processes and technologies previously discussed, much research can be done to advance this field. The following section highlights the potential in this regard to selected trends in actuator design and traditional, promising, and hybrid orthosis actuation technologies.

5.1. Orthosis actuator design

Development of orthosis actuators that contribute to the acceptance of orthoses by their stakeholders requires the iterative integration of the knowledge of engineers, clinicians, and orthosis users throughout the design process. The MIRAD (an integrated Methodology to bring Intelligent Robotic Assistive Devices to the user) research group in Flanders, Belgium has been established to do this, and has the potential to facilitate the development of formalized user centered design principles that can be generically applied to orthoses and the design of their actuators [143]. The establishment of initiatives like MIRAD is critical to providing actuator requirements that comprehensively capture technical, clinical, and user needs to aid the design of future orthosis actuators.

5.2. Current orthosis actuation technologies

The size of electric orthosis actuators has been significantly reduced through the compactness and high specific torque of harmonic drive transmissions. Further steps towards reducing the bulk and complexity of transmission can be made by focusing research on mechanically integrating frameless brushless motors with both transmission and joint load bearing elements. Brassitos et al. have demonstrated the promise of this concept in their Gear Bearing Drive actuator, which has a specific power output of 670 W/kg at 85% efficiency [144]. Portability of hydraulic and pneumatic pressure supplies has recently been addressed through the integration of electric motors and their pumps and the potential of digital switching valves to improve efficiency [145]. For example, both rotary [146] and linear [147] electromagnetic prime movers have been integrated with hydraulic pumps, such that the electromagnetic rotor or forcer simultaneously functions as a pump rotor or piston respectively. Similar advances have been made in pneumatic pressure supplies [148]. Future research on how the integration of prime movers and pump technologies can be optimized for high specific power and digital valves for efficiency will make untethered hydraulic and pneumatic actuation a promising alternative to electrically actuated orthoses.

5.3. Promising orthosis actuation technologies

Of the new actuator technologies considered in this review, DEAs have significant promise for orthosis actuation. Researchers are aware of DEAs' fundamental limitations, and are working to overcome these issues. In particular, advances have been made towards automated manufacturing processes for fabricating larger multi-layer DEAs [149], improving their reliability [150], and reducing their operating voltage [151]. Future research in this field is likely to take advantage of rapidly evolving multi-material 3D printing technologies to manufacture powerful muscle size DEAs. Related advances in additive manufacturing of tissue scaffolds could also help engineered muscle tissue to become a viable and biocompatible orthosis actuator [152].

5.4. Hybrid orthosis actuation technologies

An emerging trend in orthosis actuation is to synergistically combine multiple actuation technologies, using the advantages of each technology to complementarily overcome the others' disadvantages. Industry has already benefited from hybrid actuator technologies such as electrohydraulic actuators for aircraft control surfaces and electropneumatic actuators for low power servocontrol applications. In precision automation, hybrid nanopositioning actuators combine the long stroke of an electric motor driven ballscrew with the fine position control and high bandwidth of a piezoelectric stack (M-511.HD, Physik Instrumente GmbH & Co. KG., Karlsruhe, Germany). Hyon et al. have created a hybrid electropneumatic actuation system for a lower limb orthosis using electric servomotors and antagonistically actuated PMA [153]. The low response time of the servomotors compensates for the PMAs' relatively slow motion, and the high force output of PMAs, for the servomotors' inability to produce large torques for more than a short period of time. A novel hybrid electrohydraulic lower limb orthosis has also been developed by Saito et al. [64]. The hydraulic transmission enables a remotely located single electric actuator to control two dof, reducing complexity and mass. The use of an electric prime mover eliminates the noise, mass, and potential safety concerns of hydraulic pumps. Hybrid actuation concepts are not limited to traditional technologies, and rigid piezoelectric [154] and magnetostrictive [155] smart materials have been successfully combined with hydraulic technologies. Kinetic Ceramics Inc. (Hayward, CA) has commercialized piezohydraulic pumps with the potential to produce high specific power (above 300 W/kg) and hence be used as portable pressure supplies [156]. Given the potential of these examples, researchers should further investigate the possibilities of synergistically hybridizing traditional and new actuator technologies for orthosis actuation. Pursuing these research avenues will provide valuable contributions to orthosis and robotic actuation in general and bring us closer to realizing the enormous potential of robotic orthoses to change the lives of people with physical disabilities.

Ethical approval

Not required for this study.

Conflict of interest

The authors have no conflict of interest to declare.

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