



# A Systematic Review of Low-Cost Actuator Implementations for Lower-Limb Exoskeletons: a Technical and Financial Perspective

T. Slucock<sup>1</sup>

Received: 11 January 2022 / Accepted: 7 July 2022 / Published online: 16 August 2022  
© The Author(s) 2022

## Abstract

A common issue with many commercial rehabilitative exoskeletons and orthoses are that they can be prohibitively expensive for an average individual to afford without additional financial support. Due to this a user may have limited to the usage of such devices within set rehabilitation sessions as opposed to a continual usage. The purpose of this review is therefore to find which actuator implementations would be most suitable for a simplistic, low-cost powered orthoses capable of assisting those with pathologic gait disorders by collating literature from Web of Science, Scopus, and Grey Literature. In this systematic review paper 127 papers were selected from these databases via the PRISMA guidelines, with the financial costs of 25 actuators discovered with 11 distinct actuator groups identified. The review paper will consider a variety of actuator implementations used in existing lower-limb exoskeletons that are specifically designed for the purpose of rehabilitating or aiding those with conditions inhibiting natural movement abilities, such as electric motors, hydraulics, pneumatics, cable-driven actuators, and compliant actuators. Key attributes such as technical simplicity, financial cost, power efficiency, size limitations, accuracy, and reliability are compared for all actuator groups. Statistical findings show that rotary electric motors (which are the most common actuator type within collated literature) and compliant actuators (such as elastic and springs) would be the most suitable actuators for a low-cost implementation. From these results, a possible actuator design will be proposed making use of both rotary electric motors and compliant actuators.

**Keywords** Actuator · Assistive Devices · Cost · Lower Limb Exoskeleton · Systematic Review · Wearable Robots

## 1 Introduction

While the concept of an actuated leg attachment designed to aid in walking can be traced back to as early as 1890 [1], the first working examples are seen in 1969 with Mihajlo Pupin Institutes's "Kinematic Walker" [2] and in 1971 with General Electric's "Hardiman I" [3]. Motors and Actuation as a concept however can be traced back far further, to early Steam Engines of the 1700's for functional powered devices and all the way to the rudimentary curiosity known as an Aeolipile in the first century.

Lower Limb Rehabilitative Exoskeletons can be used to aid wearers with conditions such as Spinal Cord Injury, Cerebral Palsy, and Strokes. This can take the form of fully dictating leg movement based off of an external controller

such as for cases with heavily paraplegic patients who have little to no ability to move their legs independently, to rehabilitative or augmentative designs that encompass the leg and move based off of the user's leg movements, to more passively assistive exoskeletons for those with strokes or Cerebral palsy, who may instead suffer pathologic gait issues such as Hypo/Hypertonia (muscle limpness/stiffness) and Hypo/Hyperkinesia (poor/excessive muscle movements) but are none the less capable of some independent movement.

One of the most critical components of the exoskeleton would be the actuator, as it is these that result in the exoskeleton's movement. Actuation in its traditional form is most obviously seen in "Hard" exoskeletons, which employ sturdy, non-compliant materials in their construction, actuators are directly attach to this frame as does the user's leg, which will move with it when the frame is actuated, well-known examples include BLEEX [4] and HAL [5], they have the benefit of increase structural integrity and so can apply more force to the wearer at the cost of reduce mobility and higher inertia. "Soft" exoskeletons meanwhile are made

✉ T. Slucock  
tms40@kent.ac.uk

<sup>1</sup> School of Engineering and Digital Arts, University of Kent, Giles Lane, Canterbury CT2 7NT, England

of compliant materials and can often make use of cabling and elastics, they allow for greater mobility and are usually lighter than their hard counterparts but are less suitable for carrying heavy loads or for supporting a user who lacks the ability to support themselves as compliant materials are by their nature not as sturdy.

This paper looks to review different types of Actuators used by lower-limb exoskeletons, analyse patterns of what actuator types are most commonly used by what types of exoskeleton, as well as the costs of such actuator implementations. Additionally, this paper will cover the basic functionality of these actuator types.

Commercial exoskeletons have already been criticised as being expensive, especially for an independent consumer with average monetary availability. For example, medical spending in the UK was estimated in 2019 to be ~£2,347 per person [6] (estimates of 2020 and 2021 are anomalously high due to COVID-19 and so not included), with the costs of well-known exoskeletons such as the EksoNR costing upwards of £126,000 [7], which is infeasible for many without external funding. Even for the developed country with the highest medical spending per capita, the United States, of ~£8,369 (\$11,582) [8] per person the average exoskeleton cost far exceeds the average spending, for developing countries such as India with considerably lower medical spending and individual wealth, acquiring such equipment is effectively impossible for the average person without external funding.

As such, exoskeletons are more likely to be purchased by medical institutions who have more available capital and can then share these exoskeletons between multiple users taking part in rehabilitation sessions. While rehabilitation sessions still help to rehabilitate a wearer, pathologic gait issues often produce long-term side effects such as crouch gait which can worsen over time as a result of gradual bone and muscle damage, effects that will continue to worsen when the patient is not being externally supported. When not part of these rehabilitation sessions a wearer may have access to simpler orthoses or braces to reduce gait degradation, although these are often passive solutions that would be less able to actively adapt to the wearer. An alternative to this would be to try to create a low-cost exoskeleton that can perform basic rehabilitation and assistive actions to reduce this degradation effect while remaining capable of actively adapting to the user's needs, of the various components required for the function of an exoskeleton the actuator's cost is one of the most significant.

The actuator is a component that is often purchased multiple times for each active degree of freedom an exoskeleton supports, more actuators would naturally require a larger power supply and a likely more advanced controller to handle sending commands to them, additionally expensive, high end actuators with low latencies and high torque require a

higher quality speed controller to manage them and a more ruggedly built frame to hold them; each of these further increases the price of the exoskeleton. As such, using a low-cost methodology, if one were to use an "ideal" actuator which was of a low cost, while also providing high torque, reliability, and accuracy, with low power consumption, and an simple control system, one could considerably lower the overall cost of the exoskeleton and make it more accessible to the average person. As such this paper will compare a variety of different actuator types to judge which best fits a low-cost implementation. For consistency, all prices have been converted to British Pounds (£), while this currency was chosen due to author familiarity no special effort has been made to find the feasibility for actuator or exoskeleton purchases within the UK specifically, it is believed by the author that much of the information presented within this paper would be equally appropriate regardless of location, although prices may differ regionally. As a rough estimate of the most common conversions used within this paper: £1 = €1.20, and £1 = \$1.35, prices of components are likely to have changed between their recording and time of reading.

## 2 Research Methodology

For this paper, literature has been sourced Primarily from Web of Science and Scopus, two well-known databases of scientific journals. Papers were considered eligible if they were published after 1990 (up to June 2021), were in the subject area of Electrical/Electronic Engineering, and came from Conference Proceedings or Journal Reports. The following search procedure that has been used for Scopus is displayed below:

*Title/Abstract/Keywords: (leg OR foot OR hip OR knee OR ankle OR (lower AND (limb\* OR extremity OR body)))*

*AND*

*Title/Abstract/Keywords: (rehab\* OR assist\* OR treat\* OR pathological)*

*AND*

*Title/Abstract/Keywords: (wearable OR ortho\* OR robot\* OR exoskeleton OR actuat\* OR powered)*

*AND*

*Language: (English)*

*AND NOT*

*Title/Abstract/Keywords: (control OR classif\* OR recognition OR review OR analysis OR examin\* OR comparison OR investig\* OR estimation OR effect OR simul\* OR assess\* OR evaluation)*

This Produced 734 results, a similar search used for Web of Science produced a further 339 results, as of June 2021.

Finally, an additional 131 results were obtained through miscellaneous collection prior to the development of this paper primarily through a process of extracting possibly relevant references from other academic papers. Collectively this produced an initial total of 1204 papers, after several rounds of exclusions 127 articles were considered eligible. The Exclusion process is shown in Fig. 1, following PRISMA Guidelines.

To be eligible for partial use within the review, the remaining papers had to contain information on a lower limb exoskeleton or part of one (such as a leg or ankle orthosis), and then have some mention of the actuation method used. To be eligible for full use the exoskeleton had to specify which actuator specifically was used with enough information where one could then find details about it such as price, power requirements, weight, and so on. While similar, for the purposes of uniformity, prostheses and static walking aids such as static rehabilitation systems were not eligible as these are subject to different design philosophies. Stationary exoskeletons designed for use on treadmills, designs that made use of external connected hardware, or that only cover part of the leg such as a knee orthosis, were however permitted. In other words, Papers should be for Lower Limb Exoskeletons or orthoses that directly aid locomotion and must contain some information regarding the actuation methods and specific hardware of said exoskeleton or orthosis.

The 127 remaining papers provided enough information to determine an exoskeleton's purpose (assistive, rehabilitative, or augment), coverage (full leg, or individual hip, knee, or ankle), whether the exoskeleton was mobile (can be worn and moved around in) or stationary (limited to a treadmill), and finally what type of actuator the exoskeleton

used. Despite 127 papers describing in detail the development of their respective exoskeleton designs, none of them stated any costs associated with exoskeleton actuators or any other components, and only 25 (19.6%) provided sufficient specific detail as to the actuators used that a price could be found from further online searches (and in doing so making them “fully eligible” papers).

Other papers either failed to provide any details beyond the actuator type or provided incredibly vague information that did not state any specific brand, product detail, wattage, or so on which could be used as identifiers (for example, stating the usage of “A Brushless DC Motor”, with no further expansion). In some cases, the actuators were no longer available, were custom-made, or required contacting the manufacturer (which was done where possible), and so had no easily discoverable cost.

As seen in Fig. 2, there is a clear majority of Rotary Electric Motors, when compared to all other actuator groups, electric motors as a whole account for ~51% of all actuators. Regarding documentation quality and quantity seen in Fig. 3, there was a notable increase in usefully identifying actuator information from 2011 onwards. With only 4 out of 37 (~10.8%) papers between 1996 to 2011 containing identifiable information compared to the 20 out of 90 (~22.2%) from 2012 to 2021.

The disparity of identifiable information is further split by actuator type, with the most common actuator type, Rotary Electric Motors, which appeared in 72 (56.7%) papers, also had the highest proportion of useful identifying information, as 12 of the 25 identifiable prices were Rotary Electric Motors, with 10 of these being of the Maxon brand. This is due both to Maxon Motors being the most commonly used brand overall, with at least 30 papers directly stating the usage of their actuators, as well as motor costs and other details being freely available on the Brand's website and therefore far easier to find when compared with competing brands which often required information requests that went unanswered, leading to further bias.

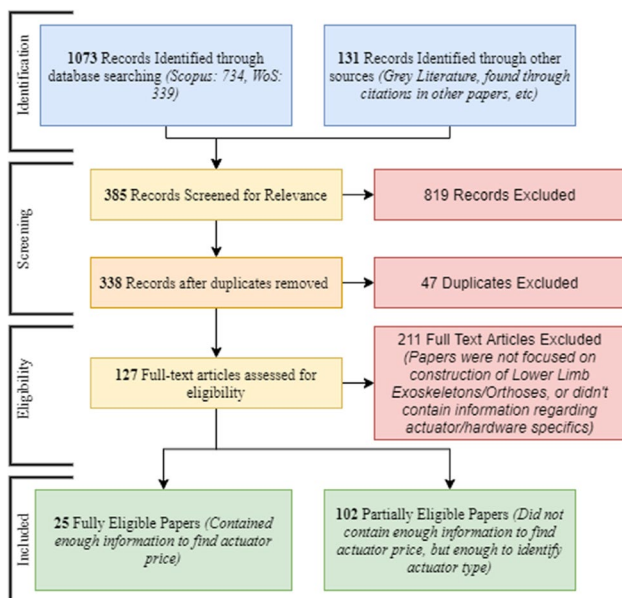


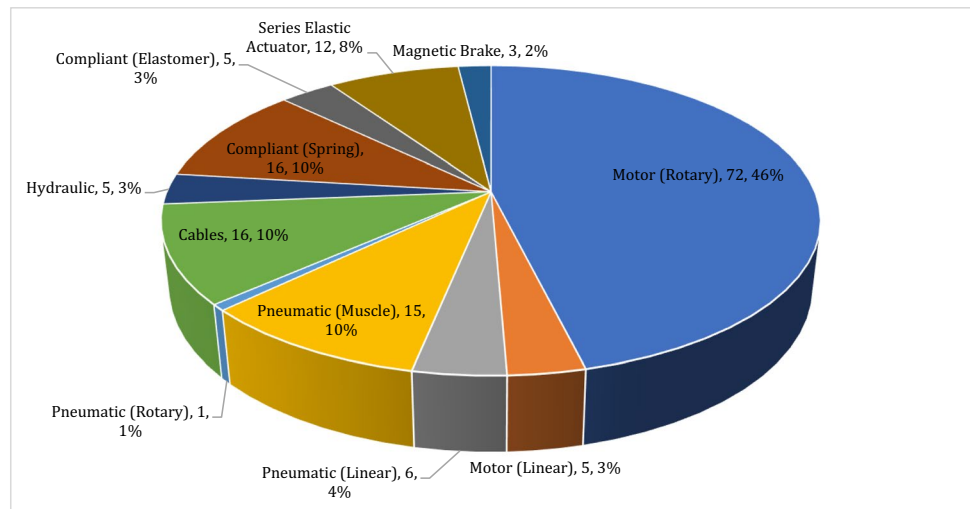
Fig. 1 Data Acquisition via PRISMA Guidelines

## 2.1 Low-Cost Implementation and Requirements

As has been discussed prior, a low-cost, low complexity exoskeleton implementation would be beneficial in reducing gait degradation as well as other pathologic issues such as crouch gait. For this paper, “Low-Cost” will refer to minimising the total financial, power, and weight costs of the exoskeleton through reducing various types of cost of its components, with a focusing on exoskeleton actuators.

**Financial cost of components:** The most obvious contributor, the overall cost of components comes from individually expensive components such as actuators or

**Fig. 2** Actuator Type Appearances Pie Chart (Note the total number of appearances is larger than total number of papers as multiple actuator types may appear in one paper, in such cases, the two most prominent actuator types are used)



the exoskeleton frame, and multitudes of less expensive components such as batteries and sensors.

*Power cost* of components: The amount of power drained by components over time, a high power cost reduces the overall use-time of the exoskeleton unless additional batteries are added, which increases financial cost and weight cost.

*Weight cost* of components: The overall weight of components, as well as the inertia they cause, a high weight cost requires more powerful actuators to overcome as well as requiring a stronger frame to support the additional weight, increasing financial and power cost indirectly.

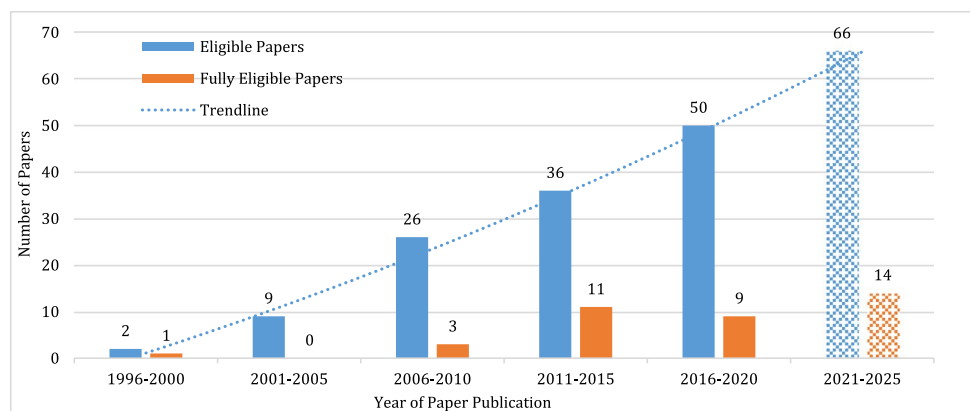
*Effectiveness* of components: While keeping costs low is ideal, if the components themselves are not effective in aiding in the assistance or rehabilitation of the wearer then they are ineffective components and not useful in the exoskeleton. As such components can be defined by how effective they are based on movement ability (how fast the actuators could move and with what force and accuracy), latency (what sort of delays may be experienced

between commands being sent and the actuator responding), durability (how much does the actuator degrade over time), controllability (how does the actuator interface with control systems) and, reliability (Actuator quality consistency, force output variance, effects of changes in environment).

Actuators will be judged by these four elements, the financial cost of their implementation as well as any peripherals they require, the power cost of their running and how power efficient they are, the weight cost on the exoskeleton as well as any peripherals they require, and their effectiveness using the metrics already defined. It will be postulated how a Low-cost implementation could be achieved if it is possible.

On top of this, the effectiveness of the actuators will be considered, with both benefits and disadvantages of each actuator type outside of Low-cost considerations. The paper will then conclude with a summary of which actuator implementations would be optimal for a low-cost implementation.

**Fig. 3** Graph of Eligible and Fully Eligible Papers, showing gradual upwards trend between 1996 and 2020, theoretical predicted increase in papers for 2021–2025 also graphed based on current trend



The Significance of these factors of effectiveness may vary dependant on the purpose of the exoskeleton, for example, an exoskeleton that is designed for sit-to-stand movements would prioritise high force output over absolute precision compared to an exoskeleton designed for correcting a pathologic gait deficiency. This paper uses a hypothetical exoskeleton designed for long-term everyday usage while remaining simple and inexpensive as its target for which actuators will be judged by. The paper will however later present a method to manipulate collected data to effectively bias it to a desired exoskeleton type or task.

While the criterium of this review paper were developed independently of other literature, a similar set of exoskeleton requirements were outlined in [9], although this paper was focused on exoskeletons as a whole as opposed to specifically actuators, similar requirements such as Cost, Weight, Reliability, and so on are considered. This paper also recognises electric motors as being the most commonly used actuator method, which is in line with the data set of this paper.

### 3 State of the Art

The following is a section containing the current state of the art as known from the previously referenced collection of papers. This does not necessarily act as a perfectly accurate representation of the entirety of the current state of exoskeleton technology, but rather can be used as one view of many. Each subsection will focus on one of the previously mentioned commonly used exoskeleton actuator methods, containing a list of some of papers collated as well as a reference to the actuators used by each, and the technology behind these actuators. Not all papers will be shown within these tables to reduce otherwise bloated sizes, papers were prioritised based on how complete the information they provided regarding actuator usage, with those with little to no information omitted from tables where possible, The Complete Dataset as well as other quantitative information can be found in the following reference [10].

The key, active actuator types, those being electric motors, hydraulics, and pneumatics, will be treated independently from each other for the sake of simplicity, in theory however multiple types could be used within the same exoskeleton, with the benefits and disadvantages of each theoretically supporting each other. Although coming at a cost to additional complexity and possibly added weight. Within the dataset there were no examples of such multi-actuator implementations although non-active actuator types such as cables and compliant actuators were seen very commonly in unison with the active actuator types, often taking the form of series elastic actuators.

Therefore, for each actuator type, a table has been made outlining some examples of that type, with as much detail as could be found within a paper, including the name and type of the actuator used, any characteristics such as the power usage, voltage, weight, and torque/force output of the motor, as well as its cost, finally, any noted peripherals required for the full function of the actuator are mentioned. These characteristics are to a degree estimated based on often patchwork information given by various papers, and as such not all actuator characteristics are available for all actuators, as some may not provide enough to explicitly define what actuator was being used. For example, a paper may state the usage of “a 74 W Maxon DC motor”, however the closest that could be found to this may be a 70 W Maxon DC motor, with several variations of different voltages, weights, and torques but all of the same price. In such an instance, the price would be noted as it is “close enough”, however all other details would be left blank due to there being no way to specify which details would be appropriate, with the exception being if they were the same across all variants.

For some other actuator types such as hydraulics cylinders or linear electric actuators where Actuator Characteristics are more lacking, approximations may be made from other, non-exoskeleton related examples or additional papers will be sourced that have such examples, these will not be counted as part of the dataset and deliberately separated from those that are.

#### 3.1 Electric Motors

Rotary Electric Motors are the most commonly used Exoskeleton actuator found by this paper, electric motors will often be designed to use their torque for high speeds as opposed to driving a large weight which is more appropriate for exoskeletons, which need high torque and relatively low speed solutions. Electric Rotary Motors can make use of gearing to improve torque and precision at the cost of rpm and increased size and weight costs, as well as reducing energy efficiency as a result of friction between gears. Table 1 displays some examples of Rotary Electric Motors from the dataset, display priority was given to those with more complete information.

##### 3.1.1 Function

As seen in Table 1, the vast majority of electric motors seen are DC servo motors, with peripherals such as a gear assembly, encoder, motor controller, and optionally a ball screw. Observing trends from Table 1, most of the electric motors range in price from £152 to £681 if purchased individually (many prices decrease when purchased in higher quantities), with further cost coming from peripherals.

**Table 1** Electric Motor Examples

Study	Actuator Type(s)	Actuator Name	Actuator Characteristics				Peripherals
			Power (W)	Volts (V)	Weight (g)	Torque (Nm)	
Neuhaus et al. [11] (2011)	BLDC motor	Moog BN34-25EU-02 I, p. 4[12]	363 W	50 V	1049 g	2.31 Nm	£ 681 [13] 160:1 SHD-20 Harmonic drive, Avago HEDL-5640#A13 Encoder, Remishaw RGH-24 linear Encoder
Marian et al. [14] (2013)	BLDC motor	Omron SGMPH-02AA6CD-OY	200 W	230 V	800 g [15]	0.637 Nm [1, p. 14][16]	100:1 Harmonic Gears, 13/16 bit encoders
Lerner et al. [17] (2018)	BLDC motor	Maxon EC-4Pole	90 W	24 V	125 g	0.045 Nm	Maxon 89:1 planetary gearbox, 3:1 Reduction Pulley, ESCON 50/5 servo controller
Baud et al. [19] (2016)	BLDC motor + Ball Screw	Maxon RE30 <sup>1</sup> , Spindle Drive 1:1 <sup>2</sup>	60 W	-	260 g <sup>1</sup> 103 g <sup>2</sup>	-	STM32F7 µC
Vouga et al. [22] (2017)	BLDC motor	Sonceboz SA SBZ-5612 [23]	-	12 V	515 g	0.32 Nm	Gates Corporation 1:1.4 timing belt, Harmonic Drive 1:100 CSD-20-2UH, STM32F7 µC
Yang et al. [24] (2014)	EC motor	Maxon EC90 flat	90 W	24 V	600 g	0.444 Nm	CTKM XB3-160 Harmonic Reducer
Zhang et al. [26] (2018)	EC motor	Maxon EC90 flat	90 W	24 V	600 g	0.44 Nm	Maxon 4095 ppr MILE Incremental Encoder, 100:1 csd 25-100-2A-GR-BB harmonic drive, Copley Accelnet digital drive
Lee et al [27] (2021)	BLDC motor + Ball Screw	Maxon Motor <sup>3</sup> + KSS SG0504 Ball Screw <sup>4</sup>	74 W	-	1120-1140 g <sup>4</sup>	-	Timing belt and pulley
Walsh et al. [30] (2006)	BLDC Motor + Spring + Ball screw	Maxon RE40 <sup>5</sup> + 115Nm/rad Spring + 3 cm Ball Screw	150 W	-	480 g	-	2:1 Timing Belt, Guide Rods, Potentiometer
Colombo et al. [32] (2000)	BLDC motor + Ball Screw	Maxon RE40 <sup>6</sup> + Steinmeyer KGT 1234	150 W	-	480 g	0.18 Nm	Toothed Belt, Gas Spring
Michmizos et al. [33] (2012)	BLDC Motor + Linear Traction Drive	Maxon EC-powermax 22-327739 <sup>7</sup> + Rohlix Linear Traction Drive	90 W	48 V	125 g	0.043 Nm	MNS9-135 Linear Encoder, Gurley Rotary Encoder
Kardan et al. [35] (2017)	AC motor + Ball Screw	Delta Electronics ECMA-C2 + Ball Screw	200 W	-	-	-	2:1 Transmission Ratio Belt and Pulley, Linear Incremental Encoder

1,2,3,4,5,6,7 Price represents component of the same number.

Many examples of electric motors producing linear motion are actually rotary electric motors paired with Ball screws. [27, 32, 35], and [36] make use of Ball Screws to convert the rotational motion of a rotary electric motor into linear motion, becoming a type of electric linear actuator. In [27], the motor is connected via a pulley and timing belt to the ball screw, that then provides the translational push–pull motion to the supported ankle. [35] uses a similar ball screw method but integrates an additional compliant spring element, the ball screw forms an inner shaft that moves a spring element that connects to the outer shaft. This compliant element is seen in series elastic actuator designs and can be used to allow for minor movements in the leg without necessitating motor movement, as well as resisting backlash. Ball Screws add additional financial and weight cost, with the example in [27] costing between £370–£420 (before VAT) [29].

Commonly used gear units include Planetary Gear sets such as the GP32 HP seen in [36] which costs ~£183.54 [37], weighs 213 g, and has a reduction ratio of 159:1, or the Banebots P61 planetary Gearbox seen in [38], costing £60, weighing 227 g, with a reduction of 26:1 [39]. Planetary gears benefit from being able to handle large amounts of torque, although a lot of stress can be placed on the structure's output shafts which need to be sufficiently durable as to avoid snapping.

The other commonly used gear set is the Strain Wave Gear (Sometimes referred to as a “Harmonic Drive”, although this is a specific brand name), such as the CSD-25–100-2A-GR-BB, used in [26], with a ratio of 100:1 and weight of 240 g, or the CSD-20-2UH used in [22] with a ratio of 1:100 and weight of 650 g, with others weighing up and over a kilogram. Harmonic Drive appear to be the brand used by the vast majority of papers employing strain wave gears in the dataset. They are known for having minimal backlash, although many can be expensive, with one example being ~£1000 [40] if purchased individually. [11, 24, 26, 41], and [42] use this gear set.

For Encoders, those mentioned within the data set can be split into two groups, the first are those developed by Maxon, such as the 4095 PPR (Pulse Per Revolution) MILE Incremental Encoder mentioned in [26]. The other group would be non-Maxon Encoders, such as the RMB28IC Rotary Magnetic Encoder in [43], or Avago HEDL-5640 A13 Encoder in [11]. Maxon Encoders in the dataset seem to cost ~£130–£150 [44], but benefit from very small profiles, being specifically designed to work with Maxon Motors, and higher precision. Non-Maxon choices however seem to be cheaper but may be less precise, for example the RMB28IC costing ~£30 [45] with a PPR of 2048 and the Avago Encoder costing £46.22 [46] but with a PPR of only 500. All encoders had similar characteristics, with low power requirements of ~5 V and 15 mA–50 mA, and weights rarely above 100 g. While the majority of encoders seen in the dataset appear to be incremental, the non-volatile absolute encoder may also be useful for exoskeleton implementations, albeit with possibly higher costs.

The final commonly required component seen is the motor driver/controller, there may only need to be one of these components to control multiple motors. [17] uses an ESCON 50/5 servo controller that weighs ~204 g and costs ~£209. Drivers may be the source of power for the actuator itself, with the prior example being designed for up to 250 W motors, as such its contribution to power is dependent on its efficiency which has been averaged to 95% (the stated efficiency of the example driver).

**Linear Actuators** Linear motors are an alternative to standard rotating motors, applying their force forwards and backwards rather than in a rotation. In Table 2, the examples both function effectively like a rotary electric motor that has been “unrolled”, with lines of alternating magnets (the stator) surrounding a mover that contains metal coils. The Baldor LMCF04C-HC0 has a U-shaped stator, with its connection point sliding on top of the U and its mover extending into it. Copley Controls' STA2508 meanwhile has a cylindrically shaped stator, with its mover sliding through the centre of the cylinder.

As with Rotary Electric Motors, Linear Electric Motors use encoders and drivers, although there are far fewer examples of each. An example that might be suitable for such motors would be the KOMP-ACT KDRV-1-MK-X-X [84], which has a weight of 160 g.

One notable similarity in these actuators is their incredibly low force outputs when compared to their weights and power usages. Unlike Rotary Electric Motors it would be far more cumbersome for them to receive any benefit from gearing and so this becomes far more of a hindrance for heavier exoskeleton designs. It is perhaps this reason that the vast majority of linearly actuated electric motors are actually rotary, making use of a ball or lead screw to convert rotational motion to linear in a far more compact means.

### 3.1.2 Summary

When looking at the literature, every rotary motor was a servo motor, with no found examples of stepper motors. This is may be due to servo motors typically being closed loop systems, allowing its current orientation to always be easily known by the control system, combined with stepper motors being less effective for both high speed and high torque situations. In situations where the motors are not combined with a series elastic actuator or other similar compliant systems however, the motor is required to move with the movement of the leg, leaving a very small latency window to prevent it resisting the movement of the user. This, combined with often large force requirements to move limb sections leads to the motors often being expensive with the commonly used Maxon Motors commonly ranging from £ ~150–~£700 per

**Table 2** Linear Actuator Examples

Study	Actuator Type	Actuator Name	Actuator Characteristics				Cost (£)	Peripherals
			Power (W)	Volts (V)	Weight (g)	Force (N)		
Emken et al. [47] (2006)	BLDC Linear Actuator	Baldor LMCF04C-HC0	-	-	320 g [49, pp. 2–3] + 1.5 kg/m roller [48]	58 N	£620 [ , p. 36]49	Baldor Lindrives (LD1A02TR-EN20), Linear Roller (THK, HSR-15R), Optical Encoder (Renishaw, RGH41)
Pietrusinski et al. [49] (2011)	Linear electromagnetic actuator	Copley Controls STA2508	744.8 W [ , p. 30]50	380 V	2.25 kg + 3.5 kg/m rod	75 N [53, p. 22]	~£750*	-

\*This price is a “best guess” based on a similar component [50]

motor; encoders, gearing, and motor controllers/drivers would compound these costs. The benefits are a more compact and relatively simple implementation when compared to hydraulics or pneumatics which are complicated as a result of fluid containment and distribution, as a result, weights of electronic motor implementations tend to be lower than similar hydraulic or pneumatic approaches.

Linear electric Motors are less commonly seen than rotary motors with the majority of linear electric actuation instead using Rotary Electric Motors in combination with ball screws. This may be a result of the size of some linear motors, for example, the Copley Controls STA2508 used in [49] was 290.5 mm long, 94 mm tall, and 54 mm wide, which would take up a lot of space on an exoskeleton. While the Baldor LMCF04C-HC0 seen in [47] is smaller, at 134 mm long, 30.5 mm wide, and 57.15 mm deep, it sits and moves on a larger rail which takes up further space and weight.

In terms of cost, linear electric motors seem to be more expensive than rotary, although the total price when accounting for peripherals evens out to, on average, be very similar as linear motors do not need gearing, rotary electric motors with ball screws similarly do not use gearing, although may still make use of timed belts, with 2:1 timed belts commonly seen connecting the rotary motor to the ball screw, this makes up for the on average lower torque motors used in these designs.

Overall, Rotary Electrical Servo Motors and their peripherals are by far the most commonly used actuators in the collected data set, with 70 of the 127 papers making use of a rotary motor in some capacity, this may be just a rotary motor on its own or used in tandem with other components as will be seen in later sections. Other types of electric motor, such as stepper motors, are less practical due to their lack of inbuilt direct feedback and so are more susceptible to drift, as seemingly evidenced through there not being any

examples of their usage within the collected data set when compared to the numerous examples of servo motor actuated powered exoskeletons. A similar claim can be made for linear electric motors (although there are at least some examples of these), as many linear actuators seen within papers are simply a rotary motor in combination with a ball screw as opposed to an actual linear electric motor.

### 3.2 Hydraulics

Hydraulics have been used most commonly in Exoskeletons designed to enhance the user’s current strength such as in industrial or military applications. This is due to hydraulics having a high power to weight ratio, although in turn have high power costs, the complexities of dealing with fluid pumping, and weights of said fluid pumps and tubing.

One of the only common factors between the limited number of hydraulic actuator examples found in the dataset is the lack of given characteristics about them. Beyond whether the exoskeleton made use single or double acting cylinders, little to no information was found for power usage, applied force, and so on. This necessitating additional examples be sought out, these are separated by a dotted line and are not considered as part of the dataset when counting the proportion of actuator types, but will be used when considering examples of actuator costs. Table 3 displays hydraulic actuator examples, as well as additional, cherry picked examples (Sun et al., Staman et al., and Wang et al.) that provide additional information but are not considered a part of any further quantitative analysis.

#### 3.2.1 Function

As with electric motors, hydraulic actuators can be both linear and rotary, although within the found literature most



**Table 3** Hydraulic Examples

Study	Actuator Type	Actuator Name	Actuator Characteristics				Cost	Peripherals	
			Power (W)	Voltage (V)	Weight (g)	Force (N or Nm)			
Saito et al. [51] (2005)	Hydraulic Cylinder, servo motor	-	50 and 30 mm cylinders				-	-	
Zoss et al. [4, 52] (2006)	Doubling-Acting Hydraulic Cylinder	-	19.05 mm bore				-	-	
Kaminaga et al. [53] (2010)	Electro-Hydrostatic Actuator (Rotary)	-	100 W	100cSt oil viscosity, 4.6 MPa operating pressure			-	Vane Motor Pump	
Kim et al. [54] (2015)	Single-Acting Hydraulic Cylinder + Spring + Servo Motor	-	-					-	Fixed displacement gear pump, proportional flow control valve, motor driver
Sun et al. [55]	Hydraulic Cylinder + Servo Motor Pump	-	340 W	-	-	1770 N at 18 MPa	-	Copley Motor controller	
Staman et al. [56]	Hydraulic Cylinder + Servo Motor Pump	Clippard H9C-6D brass cylinder <sup>1</sup> + Kollmorgen AKM22C-BCNC-00 <sup>2</sup>	290 W <sup>2</sup>	-	360 g <sup>1</sup> 1000 g [57] <sup>2</sup>	1100 N <sup>1</sup> 0.84Nm <sup>2</sup>	£36 [58] <sup>1</sup> £537 [59] <sup>2</sup>	Kollmorgen S20260 driver	
Wang et al. [60]	Hydraulic Cylinder + Servo Motor Gear Pump	Servo Motor	440 W	-	-	1570 N–2453 N at 5 MPa	-	Proportional Servo and Relief valves, 3L fuel tank	

Due to the lack of information present in the data set, additional papers (separated by the divider line) with hydraulic actuators have been found to provide it, these are not counted in the dataset as it would introduce bias, however are collated here to provide more useful information.

<sup>1,2</sup> Price represents component of the same number.

were linear cylinders. Peripheral components such as the pump, tank and valves are also required. [85]

The linear hydraulic cylinder itself consists of a piston actuated via the movement of highly pressurised fluid. It may either be Single Acting, where a fluid inlet only exists on one side (usually the pushing side), such as in [54], which benefit from simplicity due to reduced piping, but may have an unreliable force output on the non-fluid actuated side which often makes use of a spring instead. Double Acting cylinders such as those used in [52] meanwhile have a fluid port on both sides of the piston seal, and as such fluid can push the piston rod in both directions, improving reliability and stroke at the cost of complexity due to more piping and valves to switch the flow of fluid.

Hydraulic Cylinders rely on several other components to form the full hydraulic actuator, such as fluid flow controlled by valves/solenoids and pressure produced by the pump. There are three types of valves seen within hydraulic systems. Pressure control valves can act to relieve or control

pressure to reduce the chance of pressure damage within the system, direction control valves which redirect or stop fluid flow such as redirecting fluid in double-acting cylinders when they change from actuating one direction to another, and Flow control valves which regulate the rate of flow of fluid, and therefore the speed of hydraulic actuators.

The Hydraulic pump is the input that converts mechanical energy to fluid energy for a hydraulic actuator. During function pumps operate continuously at high RPM, and in a single direction. Common pump types include the gear motor and Vane motors, the pump motor itself can be a rotary electric motor that is then enclosed in the pump housing, for example [56] uses a 290 W Kollmorgen AKM22C-BCNC-00 servo motor for its pump.

The final parts of a hydraulic actuator setup are the method by which fluid is transported through its components (the pipes, tubes, and hoses) and how excess fluid is stored. Fluid is stored in a tank or reservoir, while size may vary one example seen in [65, p. 10] uses a 3L Tank weighing 400 g

for storing VG46 Hydraulic Oil. If full, this Tank would weigh an extra 2.6 kg due to this oil, with a density of  $0.87 \text{ g/cm}^3$ . The tank itself is light, and may indicate that the fluid in the tank would not be pressurised.

Electro-Hydrostatic Actuators like the one used in [53], combine the cylinder and pump into a single self-contained unit that runs on electrical power, this reduces the need for tubing and separate pumps, therefore simplifying the structure. However it still contains the same components as a regular hydraulic system.

### 3.2.2 Summary

Hydraulic Actuation sees the least usage of the major defined actuation types presented in this review, with only 5 papers reporting to use it in some capacity in addition to no available references to specific hardware or costs and very limited descriptions as to the exact functionality of the actuator implementations. From analysis, the sample size is too small to find further patterns, and as such some of the 5 exoskeletons will receive individual explanations as to their function, before then looking at information from other papers.

[51] makes use of two double acting cylinders, a master cylinder and a biarticular slave cylinder connected together such that when the master extends the slave compresses and vice versa as shown in Fig. 4. The extension and compression levels of the master cylinder are directly controlled by a servo motor via a screw that converts rotational energy

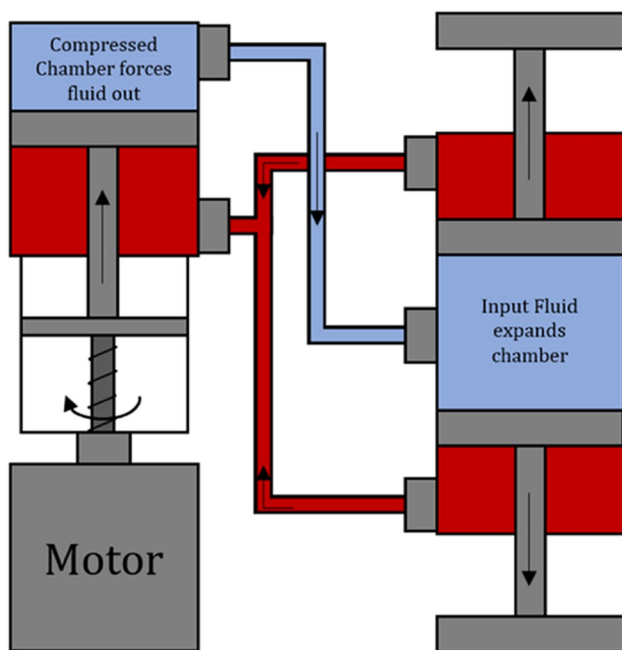


Fig. 4 Double-Acting Hydraulic Actuator [51]

to linear motion. This bypasses the need for a pump as the servo motor directly controls the level of compression of the master cylinder and therefore the extension/compression of the slave cylinder.

The lack of need for pumps, tanks and so on allow for reduced weight when compared to other hydraulic systems, although this actuator requires two cylinders instead of one. This system benefits from not needing the electric motor to run continuously to maintain pressure, only rotating when pressure needs to be changed, with the full exoskeleton using 2 of these actuators per leg, with an upper actuator for the hip and knee, and lower for knee and ankle. This may also allow the motors to be placed externally to lessen the load of the exoskeleton.

[54], Fig. 5 makes use of a single-acting linear hydraulic cylinder, with a gear pump providing fluid pressure (with its mechanical power provided by an electric motor) which is monitored by flow control and check valves. The system uses a pressure sensor to provide feedback that controls the force of the hydraulic cylinder. The system only does work during certain phases, with 4 phases in the paper described as “Negative work” such as a crouching motion where fluid flows from the cylinder to the reservoir and energy is dissipated. “Positive work”, such as a standing motion where fluid flows from the reservoir to the cylinder via the pushing action of the pump allowing the

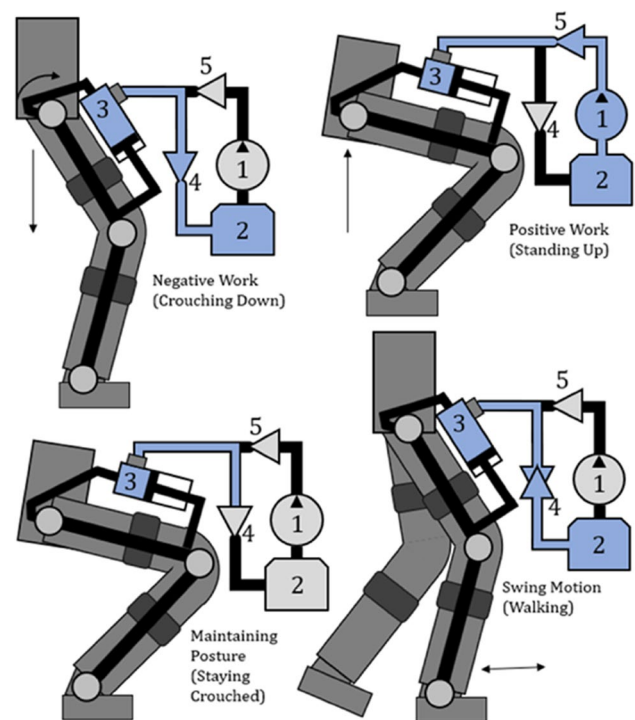


Fig. 5 Example of different phases [54]. Numbered components are: fixed displacement gear pump (1); hydraulic reservoir (2); single-acting hydraulic cylinder (3); proportional flow control valve (4); check valve (5)

cylinder to provide work to aid in standing. “Maintaining posture”, where hydraulic fluid cannot flow to the reservoir and so is stuck in the cylinder, as the fluid cannot be compressed the cylinder and piston stay at their current position. Finally, “Swing Motion” where the fluid may flow to and from the reservoir but not via the pump and so the cylinder and piston move freely. This method attempts to save energy by having the pump only be on when it needs to be.

Due to the lack of available examples within the existing dataset, effort was made to find some additional actuator characteristics, although the papers that these have been taken from have not been considered in the full list of literature to avoid introducing bias. The Hydraulic Actuation System seen in [55] provides actuation to the hip, with the whole unit weighing 2.5 kg, requiring 340 W to power the DC motor used for the pump, a rod diameter of 10 mm, and operating at a pressure of 18Mpa, this results in a maximum thrust of 1770 N, a normal torque of 0.8Nm, and peak torque of 1.8Nm. This system uses 4 of these Actuation systems, with a separate power unit weighing a further 16.6 kg, bringing the total mass of the exoskeleton to 26.6 kg.

Another example called “PREHydrA” [56] states example components used, including a Kollmorgen AKM22C-BCNC-00 0.84Nm, 290 W servo motor for the pump estimated to cost ~£537.57 [59] and weighing ~1 kg [62, p. 21], this was driven by a Kollmorgen S20260 weighing 770 g [67, p. 17], estimated to cost ~£725 [86] and a Clippard H9C-6D brass cylinder for the hydraulic cylinder, this cylinder had a weight of 0.67 kg and cost of £36. It was used to produce up to 1100 N of force [58].

From a low-cost perspective, Hydraulics would likely not be applicable within rehabilitative or assistive exoskeletons. While claims are often made to hydraulics possessing high power to weight ratios, this may simply be referring to the hydraulic cylinders’ weight when compared to the force it is capable of putting out when connecting to a powerful pump system which is more easily placed elsewhere where it would not contribute to the weight of the actuator. However, as an exoskeleton has to carry all hydraulic peripherals with it rather than being able to store them on separate, more stable platforms as with the traditional industrial equipment that most commonly sees hydraulic usage, each peripheral would instead contribute to the mass of the overall exoskeleton, it quickly becomes impractical for a preferably light-weight system that would instead have to carry a bulky pump and battery pack to remain functioning. As many of these pumps seem to rely on an electric motor already (albeit such a motor would not require high precision or low latencies) it effectively adds a lot of extra complexity which while beneficial for providing a higher force does so at too much of a cost in weight and power usage for a specifically low-cost implementation.

Additional issues of a hydraulic actuator include its noise, potential of leakages and spillage as a result of malfunctioning piping, and high levels of maintenance due to many rapidly moving parts, all of which would be a mark against it for use in rehabilitative, at-home exoskeleton implementations, although may be less important for industrial, augmentative exoskeleton implementations.

### 3.3 Pneumatics

Pneumatic actuation is similar in nature to hydraulic actuation, however it makes use of compressed inert gases as opposed to liquid. A Valve allows compressed air in from a container to increase pressure within a piston or diaphragm to cause it to extend, or air out (returning to a secondary chamber or vented) to decrease pressure and cause it to contract. Table 4 and Table 5 display Pneumatic Cylinder and Pneumatic Muscle Actuator examples respectively.

#### 3.3.1 Function

**Pneumatic Cylinders** Pneumatic Cylinders are a rigid linear actuator that can be extended or retracted through changing the pressure of the compressed gas within. It is similar to a hydraulic cylinder, although unlike fluids, gasses are compressible and therefore not as effective at transferring input energy to output mechanical motion, the benefits are however that it may be compressed into a smaller reservoir, and possesses a superior flow rate even at lower pressures due to far lower viscosities when compared to hydraulic fluids, finally the gas does not need to be forced to flow via a pump as long as there is a sufficient pressure differential between the desired source and destination. One key disadvantage however is that for a piston to retract into a chamber already filled with pressurised air, the air must be vented otherwise the piston rod’s movement would be resisted, as a result the volume of air in the system decreases with continued usage, and so the pressure in the system decreases over time so decreasing output force. A method of air recompression may be used to counteract this and refill a storage tank, the exoskeletons in [63] and [69] used an external compressor for testing purposes, however ideally a smaller on-board implementation such as a Micro-compressor, Diaphragm Compressor, or some other method [87] could be used. While none of the examples directly mentioned a traditional on-board compression method, one less traditional method in [61] used dry ice, as it sublimates directly into carbon dioxide it allows for the storage of gas as a far denser solid, although not requiring direct power this method works only as long as there is enough dry ice to ‘fuel’ it.

Single-Acting Cylinders see use in [61] and [68]. Double-Acting Cylinders (DAC) meanwhile see examples of

**Table 4** Pneumatic Cylinder Examples

Study	Actuator Type	Actuator Name	Actuator Characteristics		Cost	Peripherals
			Weight (g)	Force (N or Nm)		
Wu et al. [61] (2007)	Single Acting Pneumatic Cylinder	Fujikura BF cylinder	1500 g	-	[62]	SMC ITV2051-212 s Pneumatic regulator
Sato et al. [63] (2011)	Double Acting Pneumatic Cylinder	Inner diameter 32 mm, 200 mm stroke	-	-	£ 107.72* [64]	Electro-pneumatic regulator
Li et al. [65] (2013)	Rotary Pneumatic Actuator	Parker Hannifin, PRN30D-90-45	480 g	2.7–16.6 Nm (0.2–1 MPa / 30–145 PSI) [66]	£ 284.75 [67]	JacPac J-6901-91 CO <sub>2</sub> Bottle with pressure regulator, Festo LRMA-QS-4 Pressure Regulator, Festo VOVG 5 V Solenoid
Yamada et al. [68] (2014)	Single Acting Pneumatic Actuator	-	-	-	-	Nihon Pisco SEU11-6A pressure sensor
Zheng et al. [69] (2019)	Double Acting Pneumatic Cylinder	Bimba Manufacturing 173.5-DPY,	-	1965 N (250 PSI / 1.72 MPa)	£ 44.42 [70]	Sizto Tech 2S020-1/8A solenoid valves, Pneumadyne PNV11-66 Needle Valves, Dura Pro SLP air tank

\* This value is a “Best guess” based off of limited information.

implementation in [69] as the knee actuation method for a sit-to-stand device, this method connects the pneumatic cylinder between points on the lower leg and upper leg on an exoskeleton that hinges at the knee, with its positioning such that it is naturally facing upwards when the user is sitting down. When the user wishes to stand the pneumatic cylinders are enabled via solenoid valves to assist in this action by pushing up on the upper legs, needle valves then control the speed of the pneumatic cylinders to best assist the wearer. This system does not run into the issues of the unreliable pulling force of a single-acting cylinder as it only needs to be used in pushing actions, with it simply remaining passive if the user contracts their legs to sit back down. Another example would be [63] where a full-body exoskeleton is used to augment arm and leg joints, to aid in the action of lifting heavy objects.

An additional implementation seen used within exoskeletons is as part of a pneumatic rotary actuator such as [65]. Rather than having the cylinder itself push and pull in the exoskeleton, two small cylinders (or one double-acting cylinder) either side of a gear wheel, connected by a toothed rack that runs across the gear. This converts the linear motion of the pneumatic cylinder into rotary motion that can drive the joints of an exoskeleton.

**Pneumatic Muscles** Pneumatic Artificial Muscles (PAMs), were first developed in the 1950’s under the term “McKibben Artificial Muscles”. These lightweight membranes hold compressed air, when at high pressure they will expand widthways and contract lengthways, when at low pressure

they can stretch lengthways and contract widthways. The strength of these is based upon the strength of the woven membrane and the air pressure used. Effectively by pumping air into them they will contract, pulling the objects connected at either end closer together.

McKibben Muscles (or similar implementations) see usage in exoskeleton examples such as [73, 88–90], and [91]. These muscles have the issue of only being able to effectively pull and not push, meaning that if one wished to actuate a knee joint for example, two pneumatic muscles would be needed for each degree of freedom. An Implementation such as [89] uses of two PAM’s connected at either end of a cable and pulley system such as Fig. 6. When either one contracts it pulls the cable along with it, and pulling up the other side. If the pulley is then connected to the relevant joint the muscles can be used to control its rotation by either expanding or contracting.

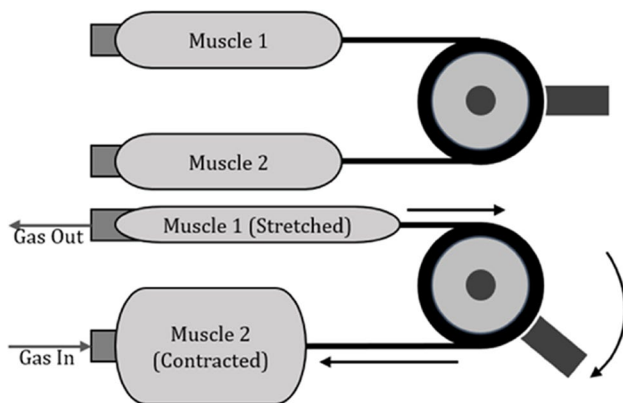
Another type of Pneumatic Muscle is shaped more like a series of thin sections attached together rather than a straight tube (Fig. 7). Each section expands while attached to some kind of stiff yet still compliant surface attached on one side. When the muscle expands, it will attempt expand out to a straight position and therefore cause the surface to bend, changing its angle. These have seen use in exoskeletons to aid in abduction/adduction and flexion/extension. They are also seen in papers such as [79] and [81] which use a bubble-like strip of PAMs attached to the knee and ankle respectively to act as walking aids, when

**Table 5** Pneumatic Muscle Examples

Study	Actuator Type	Actuator Name	Actuator Characteristics		Cost (£)	Peripherals
			Weight (g)	Force (N)		
Yamamoto et al. [71](2007)	Fluidic Muscle	Hitachi Medical Air Muscle	-	-	-	Servo Valve Regulator
Chandrapal et al. [72](2009)	Fluidic Muscle	Festo DMSP Fluid Muscle	-	-	-	-
Park et al. [73] (2011)	Fluidic Muscle	Festo DMSP-10-(120/140/160)-RM-CM	190 g -230 g [74]	480 N at 0.6 MPa [75]	-	Parker Hannifin NEX-2-03-L Solenoid valves
Sasaki et al. [76] (2012)	Inflatable Actuator	85 mm x 80 mm x 0.6 mm Aluminium film balloons;	-	-	-	External air compressor
Sasaki et al. [77] (2013)	Textile Inflatable Actuator	Okenseiko RFP32B03R rolling air pump, 140 mm diameter rubber/cloth balloons	-	-	-	Pressure Sensors and Flow Meters
Chung et al. [78] (2018)	Textile inflatable actuator	Fiberglast Thermoplastic polyurethane (TPU), Seattle Fabrics Nylon	-	-	-	Humphrey solenoid valve 320 12VDC, Honeywell 100PGAA5 pressure sensor, D55146 Compressor
Park et al. [79] (2020)	Textile/ thermo plastic inflatable actuator	Jinheung Industry JTC1003 thermoplastic polyurethane (TPU) film,	13.4 kg [, p. 18][80] <sup>1</sup>	-	Est. £350 [80] <sup>1</sup>	Grünhain PSE540-M5, SMC Pressure gauges, SMC Co PFM750S-C6-C flowmeter, SMC Co ZU05SA vacuum ejector, Elektromotorenwerk ECS 80G 4-213 EMG Compressor <sup>1</sup>
Thalman et al. [81] (2020)	Textile inflatable actuator	200 Denier Rockwoods nylon Fabrics <sup>1</sup> +thermoplastic polyurethane <sup>2</sup> (TPU)+	110 g/m <sup>2</sup> <sup>1</sup> 1.21 g/cm <sup>3</sup> [82] <sup>2</sup>	-	~£3.60/m [83] <sup>1</sup>	Humphrey solenoid valve 320 12VDC, Model 8010A Compressor

<sup>1,2</sup> Price represents component of the same number.

filled with air they expand outwards and so can help to extend the knee or ankle, then when air is taken out they contract and allow the knee and ankle to flex. A different



**Fig. 6** Fluidic Actuator

implementation is seen in [76] and [92] which use single, large inflatable pads placed on the back of the upper and lower leg and the front knee, connected via a non-compliant cloth which also attaches to the leg, when inflated they help to contract the knee by changing the cloth angle.

Both Pneumatic Cylinders and Muscles require a source of pressurised gas in order to function, this in turn requires Solenoids to block/redirect the gas, air tanks to store it, and compressors to pressurise it.

Example solenoids such as the Festo 5 V VOVG Solenoid used in [65], Sizto 2S012-020 in [69], and Humphrey Series 320 in [81] have been used in order to control the flow of pressurised gas within both pneumatic cylinders and muscles. Some of these designs, such as the VOVG Solenoid are modular, and as such their weight and size do not increase entirely proportionally with the number of valves, starting at 84 g for 2, they increase by ~ 21 g per additional valve [99, p. 17]. Prices of solenoids can vary, with the Sizto 2S013-20 costing ~£24 [93], while the

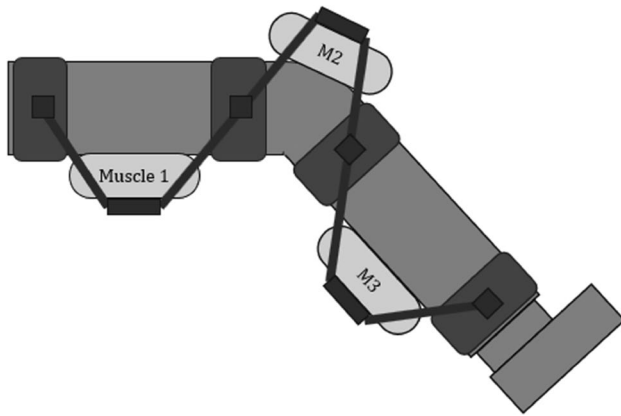


Fig. 7 Redrawn Inflatable Actuator [77]

Humphrey Series 320 costs [94]. All three solenoids are capable of or have variants that can run at 12VDC, as well as varying between ranges between 5 to 24 V.

Example Air tanks include the Dura Pro SLP Tank used in [69], this tank is capable of storing pressurised gas at 4500 PSI, which is much higher than the 250 PSI used by the Pneumatic Cylinder, this may allow it some limited function without a compressor by storing gas at a much higher pressure than is needed, such that as pressure decreases with the used up gas the system can still function, although this puts a hard limit on the amount that the cylinder can be used before needing to be refilled. However to hold such high pressures the tank must be strong enough to hold it, increasing weight, this example being ~1.2 kg [95] and costing ~£148. The tank itself must also have an output pressure higher than the pressure of the pneumatic cylinder, otherwise it would act as a bottleneck, this example having a 300psi output pressure.

Compressors are the component that causes the most concern for the feasibility of low-cost pneumatic actuators, especially pneumatic cylinders, as all examples within the dataset make use of external compressors, which in every case are impractically heavy for an actual, real-world exoskeleton. With some examples including the DeWALT D55146 225 PSI Compressor [96] used in [78], the Elektromotorenwerk ECS 80G 4–213 EMG Compressor [97] used in [79], and the California Air Tools 8010A [98] used in [81]. Each of these have output pressures varying from 120 to 225PSI, but require power in the kW's, have weights between 16.8 kg–37.7 kg, and noise outputs between 60–78 dB (60 dB ~ = sound of a conversation, 78 dB ~ = sound of a vacuum cleaner). These devices would be impractical for continual home use due to all of the above factors, except if used as a place where a user could “refuel” an on-board gas tank, or replace an empty one with a pre-filled one. Small, compact compressors do exist, such as the Nitto Kohki DAH 110 [99] or the TOPSFLO TMD45A-A [100], both with voltages of 12–24 V and weights at or just below 1 kg.

However both of these have much lower output pressures of 15 and 56.5 PSI respectively, this would, at most, be able to provide enough pressure to textile inflatable actuators. The costs of these compressors average to ~£160 [101] [102].

### 3.3.2 Summary

Pneumatic Cylinders are capable of providing a lot of linear force to aid in moving a person's limbs, and so have seen use in assisting sit-to-stand or other crouch-based manoeuvres which require high levels of force. When compared to rotary motors they can be relatively cheap, with an off-the-shelf £44 cylinder [70] used in [69] capable of outputting a considerable 1965 N. When compared to rotary motors, a 420 W Maxon EC-I motor over 10 times the price can have a torque of up to 1.04Nm to achieve a similar force when attached 10 cm from the knee joint a 188:1 gear shaft would be needed. However in order to achieve this force the gas would have to have first been pressurised to 250 PSI and stored, meaning some kind of compressor is required to pressurise the gas, however all examples capable of producing high enough pressures are too large to be fitted to an exoskeleton. Limiting the feasibility of this exoskeleton type within rehabilitative scenarios, unless contained within some kind of movable trolley or as previously stated used as a refuelling point, although if it were used as a refuelling point, it would be essential for the gas tank to be able to be able to provide pressurised air to the exoskeleton for at least a few hours, the capacity of such a tank may need to be considerable.

While cylinders can provide considerable power, it comes at the cost of weight and space with the distance the rod can travel (the stroke) being tied to the length of the cylinder itself, this means that a longer stroke will take up a lot of space and weigh more. Additionally, a cylinder alone is useless, requiring additional components such as solenoids, piping, air tanks, and compressors adding further weight, complexity, and cost.

Pneumatic Muscles on the other hand have found usage within soft exoskeleton designs due to their relatively low weight and compliance allowing for unrestricted movement. They can directly attach to hardpoints near to where weaker muscles are located. Pneumatic muscles are also capable of providing somewhat significant force, for example the FESTO DMSP-10–120-RM-CM used in [73] claims to provide up to 630 N of force at maximum operating pressure. However as previously mentioned this is limited to a single degree of freedom, and so at least two would be needed for full actuation.

One flaw that affects pneumatic actuators as a whole would be the delay between commanding the actuator to increase or decrease in power and it actually happening, as it inevitably takes time to build up or release pressure, this

is more of an issue than with hydraulics, due to gas being compressible.

### 3.4 Cables

Cables are rarely used by themselves within the literature, but instead in tandem with other actuators to reduce the inertia that needs to be overcome when applying force to limbs by shifting the placement of the actuators themselves and instead transferring force via cables. This allows the legs to be lighter due to a lack of actuators and so less inertia to be

overcome. Table 6 displays cable actuator examples, which often make use of additional active actuator methods such as Electric Rotary Motors.

#### 3.4.1 Function

Bowden Cables use a hollow sheath which allows for a cable to slide through it. When an actuator exerts force on the inner cable it will slide within the sheath and transmit the actuated force from one end to the other even when the sheath is at an angle. With softer, elastic materials such as

**Table 6** Cable Examples

Study	Actuator Type	Actuator Name	Actuator Characteristics				Cost	Peripherals
			Power (W)	Volts (V)	Weight (g)	Torque (Nm)		
Veneman et al. [115, 116] (2006, 2007)	Bowden Cables + Servo Motors + Linear Actuators	4 × 1.5 m Bowden Cables Kollmorgen AKM22C <sup>1</sup> Berger Lahr SER3910 <sup>2</sup> Linmot P01-37 × 240 <sup>3</sup>	567 W <sup>1</sup> 690 W <sup>2</sup> 250 W <sup>3</sup>	-	1080 g <sup>1</sup>	0.87 Nm <sup>1</sup>	-	Neugart Planetary Gearheads (64:1 and 8:1)
Asbeck et al [107] (2013)	BLDC Motor + Bowden Cables	Maxon EC 4-pole 30 <sup>4</sup> , Nokon # KON05020 Cables	200 W <sup>4</sup>	-	300 g <sup>4</sup>	0.092 Nm <sup>4</sup>	£598.20 [117] <sup>4</sup> £76 [118] <sup>5</sup>	Copley motor Controller, 111:1 gearbox
Mooney et al. [103] (2014)	EC motor, Cable	Maxon EC-4pole (305,015), 1 mm diameter Dyneema polyethylene cord	200 W	48 V	300 g	0.093 Nm	£ 606.45 [119]	13:8 belt transmission, Maxon HEDL 5540 Encoder, Roboteq SBL1360 motor controller
Jin et al. [105] (2015)	BLDC Motor + Cables	Kollmorgen AKM43 servo motor + Nylon coated steel wires	-	-	-	-	-	-
Schmidt et al. [110] (2017)	BLDC Motor + Cables	Maxon EC-i40 + Dyneema / UHMWPE 0.6 mm cable	70 W	-	-	-	£207.31 [120]	Encoder and Motor Controller
Lee et al. (2019) [106]	BLDC Motor + Steel Cables	Maxon EC-I brushless motor <sup>6</sup> + Carl Stahl Sava Industries steel cable 2081 <sup>7</sup>	75W <sup>6</sup>	48V <sup>6</sup>	24 g/m <sup>7</sup>	-	£195.22 [121] <sup>6</sup> £3–3.75 / ft [113] <sup>7</sup>	Maxon DCX10 Rotary Cam
Mioskowska et al. [108] (2020)	Pneumatic Cylinder + Bowden Cables	CHLED SC40X75 air Cylinder, 37.5 mm bore, 77 mm stroke	-	-	-	-	-	12 g CO <sub>2</sub> cartridge
Bryan et al. [104] (2020)	BLDC Motor + Bowden Cables	10 Kollmorgen AKM74P Motors <sup>8</sup> + West Marine, V-12 Vec-tran Single Braid inner cable; Lexco 415,310–00 outer cable. <sup>9</sup>	700W <sup>8</sup>	-	-	-	£1.50–2 / ft [114] <sup>9</sup>	Kollmorgen AKD-P02407 Motor

<sup>1,2,3,4,5,6,7,8,9</sup> Price/Characteristics represent component of the same number.

nylon and polyurethane like those used in [103] and [104] the actuation system can only react to pulling motions, meaning two cables may be required for bi-directional movement. Stronger materials such as stainless steel can be used such as in [105] and [106], the strength of the steel allows for transmission of both pulling and pushing motions, although sacrificing some flexibility. In terms of cost, while examples are limited, braided cables such as those used in [104] are slightly cheaper and lighter (~£1.50-£2) than equivalent thickness steel cables such as those used in [106] (~£3-£3.75).

Within the acquired literature, Bowden Cables saw a large amount of use, seen both in mobile exoskeletons such as [107] and [108], and stationary such as [104] and [105]. The Mobile exoskeletons often transferred power from actuators placed in backpacks to reduce inertia on the user's legs, while stationary examples lightened the weight of the exoskeleton all together by using cables to transfer power from external motors not placed on the exoskeleton, with the user walking on a treadmill to remain stationary. Such an implementation benefits low-cost implementations in many ways, as actuators can be placed out of the way to less restrict movement. Although a stationary exoskeleton would not be as useful in every-day usage.

**Pulleys** Cables that make use of a pulley less from the issue of friction as the pulley itself can rotate with movement of the cable, this pulley can be rotated to move the cable. This method requires the cable to always be tensioned as to not slip off the pulley. Implementations may include having an endless cable that forms a belt-like loop between two pulleys, a rotary actuator could then apply a bi-directional force to rotate one pulley, moving the cable and so rotating the other pulley. The cable will usually be wrapped around these pulleys multiple times to increase friction between it and the pulley, as in [109], using an endless cable drive to transmit actuator force from the central walker to the exoskeleton itself. The cable may also be open ended, in which case the cable connects to end points with the pulley as the intermediate point, these endpoints may be direct connections, connections via a spring, or actuated connections, the pulley itself can also be an endpoint, with the cable attached such that the pulley can be rotated to pull the cable in or release it out. Other mobile pulley systems that did not make use of walkers include [110, 111], and [112].

### 3.4.2 Summary

Cables will often not be used on their own, as every noted example in Table 6—Cable Examples makes use of active actuators alongside them, with the vast majority being rotary electric motors. This does not cables being a potential low-cost technique, with cabling itself having a negligible cost

with quoted costs of £3–3.75/ft [113] and £1.50–2/ft [114] respectively, although these are for bulk orders of 100–250ft which were seen as standard minimums. These examples were from cables providers used in [106] and [104]. The cables can take the place of some actuators, such as is used in [110] where a single 70 W Maxon EC-i40 electric motor is used for each leg, connected to a cable that connects via pulleys from the front leg shank around the back of the upper leg and eventually connecting at the hip. The motors can then loosen or tighten the cables to let the user's legs down or pull them straight. Compliant elements then hold the front upper leg and back lower leg. Therefore, one motor can assist the entire leg, albeit not as precisely as an entirely motorised system, but with the benefit of lower power usage, cost, and possibly (heavily dependent on implementation) weight. The exoskeleton in [110] weighed 4.6 kg with batteries, which is considerably lighter than some fully motorised implementations.

## 3.5 Compliant Actuators

Compliant Actuators refers to a variety of miscellaneous actuation methods that make use of elasticity to contract and extend or compress and expand in order to move part of an exoskeleton. Table 7, Table 8, and Table 9 refer to examples of Spring Actuators, Compliant Materials, and Magnetic Breaks, actuator methods, which may be used alongside other more active actuator implementations.

### 3.5.1 Function

**Springs and spring-equivalents** The elasticity of the spring itself can also store some energy, this in particular is useful for legged locomotion such as exoskeletons as a leg outstretched or contracted with a series elastic actuator could partially return to an unstretched position through the natural contraction of the elastic, saving energy as there is no need for a powered actuator to do it. This process can also be used for fully or partially passive exoskeleton implementations.

Springs require no electrical power and provide an increasing force the more they are either extended or compressed, as long as the force applied does not result in inelastic deformation. Such Implementations are seen in [122, 126], and [144] which directly use springs or spring-like devices as actuation for knee and hip joints. Such a system would seem excellent from a low-cost perspective, as springs have both low financial and weight costs, requiring no additional batteries or other peripherals. However, on their own a spring can only provide a set force dependent on how compressed/extended it is, while capable of fulfilling a basic assistive role it would not be able to adapt to the needs or situation of the wearer.



**Table 7** Spring Actuated Examples

Study	Actuator Type	Actuator Name	Actuator Characteristics				Cost	Peripherals
			Power (W)	Voltage (V)	Weight (g)	Force (N or Nm)		
Banala et al. [122] (2006)	Passive Gravity Balancing Spring	-	-	-	-	-	-	-
Wiggin et al. [123] (2011)	Spring	-	23.4 N/mm	-	-	-	-	Ratchet and Pawl system
Ranaweera et al. [124] (2018)	Spring	-	5875 N/m stiffness	-	-	-	-	-
Zhou et al. [125] (2021)	Torsional Spring	-	270Nm/Rad	-	-	-	-	-
Pengfan et al. [126] (2021)	Spiral Spring	-	0.2Nm/degree	-	-	-	-	-
Giovacchini et al. [127] (2015)	BLDC Motor + SEA Spring	EC60 Maxon Motor <sup>1</sup> + Custom Torsional Spring <sup>2</sup>	100 W <sup>1</sup>	24 V	470 g [128]	100 Nmm/rad <sup>2</sup>	-	1024 PPR MILE Incremental Encoder, 80:1 CPL-17A-080-2A Harmonic Drive
Kai et al. [129] (2014)	BLDC Motor + SEA Spring	RE-40 Maxon Motor <sup>1</sup> + Tokai-bane Torsion Spring <sup>2</sup> + MISUMI VUR8-20 Compression Spring <sup>3</sup>	150 W <sup>1</sup> [130]	24 V <sup>1</sup>	480 g <sup>1</sup>	177 Nmm <sup>1</sup> 19.8Nmm/deg <sup>2</sup> 3.53 N <sup>3</sup>	£334 <sup>1</sup> £2.16 <sup>3</sup> [131]	KHK Worm Gears and KHK Worm Wheel, MISUMI MRDM-W Rotary Damper
Alouane et al. [132] (2019)	Motor and Torsional Spring	-	-	-	-	-	-	-

<sup>1,2,3</sup> Price/Characteristics represent component of the same number.

For example, if the wearer were to sit down rather than stand up, it would be expected that their knees would naturally rest at a 90° angle as opposed to 180°, a purely spring-based exoskeleton designed for assisting walking while standing would provide considerable resistance to a wearer attempting to sit down and prove more of a hindrance than help.

A way of adding a level of control without adding power is explored in papers such as [123] and [124] which make use of locking mechanisms like a clutch. For example, a ratchet and pawl mechanism in Fig. 8 linked to the spring by a wire. At maximum gait dorsiflexion the ratchet and pawl mechanism prevents the wire from being pulled downward by the spring, as the foot plantarflexes to a flat position the

**Table 8** Compliant Material Actuated Examples

Study	Actuator Type	Actuator Name	Actuator Characteristics	Cost	Peripherals
Nikitczuk et al. [133] (2005)	ER Fluid	Electro-Rheological Fluid: ERF-3356S; Springs	-	-	-
Jamaal et al. [134] (2006)	Elastomer	Carbonyl iron particles (168 g) and low viscosity Silicone oil (31 g)	-	-	-
Li et al. [135] (2016)	Elastomer	PVC powder; dibutyl adipate (DBA) plasticizer; tetrahydrofuran (THF) solvent	-	-	-
Cheng et al. [136] (2020)	Elastic Knee Brace + Shape Memory Material	8 × Yoshimi Inc. Nickel-titanium Shape Memory Alloy Wires. <sup>1</sup>	22 cm length, 1.8 mm diameter	(C) £~10 [137] (P) £21.80 [138]	Mueller Sports Medicine Knee Brace (54,557) <sup>2</sup>

**Table 9** Magnetic Brake Examples

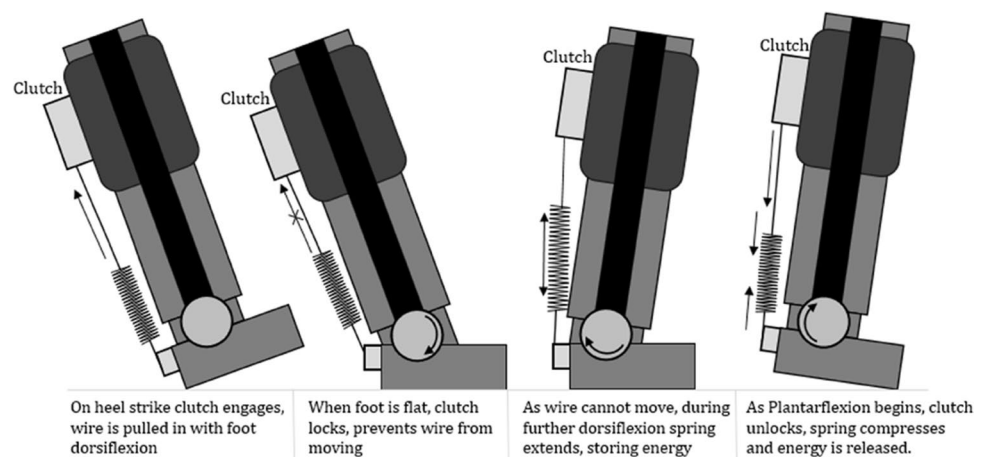
Study	Actuator Type	Actuator Name	Actuator Characteristics				Cost	Peripherals
			Power (W)	Volts (V)	Weight (g)	Torque (Nm)		
Yoshizawa [139] (2008)	Electro- Magnetic	Neodymium pillar magnets; 0.8A solenoid electromagnet	0.8A	-	-	10 N	-	Kawamura GISHI AFO
Washabaugh et al. [38, 140] (2016, 2018)	Permanent Magnets	Two pairs of 2 kJ Magnetics DX04B-N52 Magnets	-	-	-	-	£5.59 [141]	P60 Banebots 26:1 Planetary Gearbox and Aluminium disc
Chaichaowarat et al. [142] (2020)	Electro- Magnetic	Sinfonia electro-magnetic brake (PB-260/FMS-AG)	9.7 W	24 V	550 g	7Nm	£ 189.26 [143]	-

wire is still allowed to go upwards and so the slack is taken. When the foot begins dorsiflexion again the clutch locks, meaning the spring will be stretched from the movement of the leg as the wire cannot move, it reaches maximum stretch just prior to push-off. When the foot pushes off the spring contracts again, aiding in plantarflexion. Once the spring is contracted fully the clutch unlocks and the wire moves freely to reset the system.

For softer exoskeleton designs, elastic belts can be used instead of springs. While unable to provide a pushing force they are still capable of pulling if stretched, as seen in [145] where a stiff belt on the upper leg connects to the knee, wraps around the lower leg to the back in an inverted-Y shape, and attaches to the calf and bottom of the heel. The system aids in ankle plantarflexion and knee flexion by using a DC motor to pull on the belt. As with cabling, compliant actuators can be used to extend the reach of a limited number of motors to decrease weight and financial costs at the sacrifice of precision effectiveness.

[127, 129], and [132] make use of Series Elastic Actuators, a combination of a rotary motor with a compliant

element (spring, elastic, muscle, etc.) in series with it. The compliant actuator can take some of the strain off of the motor, allowing it to better deal with sudden bumps and changes as the compliant element can compress and extend, absorbing impacts in the process. The elastic aspect is achieved in [127] through a torsional spring of stiffness 100 Nm/rad, this is attached in series with the rotary motor such that the motor does not have to move exactly with the motion of the hip. Torsional Springs as well as Compression Springs and other series elastic actuator implementations come with the cost of limiting maximum actuator force due to loss of energy from the spring, reduced precision in controlling exact force amounts, and increased complexity [146]. They can however be inexpensive ways to improve the durability of an actuator through shock and backlash absorption, as well as allowing for larger latencies and lower precision motors to be used as the compliant actuator can respond instantly and make up for minor positional differences. The weight cost of a spring can often be considered negligible unless weight is of critical importance, for example the system within [127] had a total actuator

**Fig. 8** Redrawn Clutch Mechanism [123]

weight of 1.2 kg, of which the spring was likely a relatively small percentage of.

**Compliant Materials** Artificial muscle could be seen as a semi-elastic cable that is capable of squashing and stretching to mimic the flexing of a biological muscle. There are several different existing examples of this technology.

Pneumatic muscles have been discussed in a prior section, other similar examples include Dielectric Elastomers [147] which make use of an electrostatic attraction between conductive layers, these can cause a compressive strain on each other when an electric field is applied to them. It has a constant volume, and so when compressed together in one plane, will expand in the other two. By then restricting one of these planes most expansion will occur in one direction perpendicular to the compression. Usages within exoskeletons include [135] which uses PVC gel pads attached to a belt that runs from the hip to the knee, when these pads expand outwards they contract sideways shrinking the belt and so aiding hip flexion, and [148] which uses a bellows shaped constraint filled with polyimide fibres, in a similar belt structure connected between the knee and ankle. When activated these expand to provide dorsiflexion assistance to the ankle.

Another compliant material would be shape memory alloys, these alloys usually can be deformed at low temperatures, then when heated revert to their original shapes. However, in [136] a nickel-titanium alloy is kept in a state of superelasticity (aka pseudoelasticity) that occurs between the Shape Memory Alloy's hot, difficult to deform austenite memory phase where the material will recover from any already existing deformities and the cold, more easily deformable martensite phase, there is however an in between area, as it requires a higher temperature to go from martensite to austenite than it does to go back down from austenite to martensite. Superelasticity means that the material is deformable under strain, and will recover when not under strain.

**Magnetic Brakes** Magnetic Brakes, while not strictly compliant, they can be used in a similar role to compliant actuators. As seen in [140] and [142], A magnet is placed in parallel with a spring plate as part of the brake rotor, when the electromagnet is activated, the rotor moves to be in contact and impart friction on the brake stator which causes resistance to joint movement. By varying the voltage applied to the electromagnet the resistance can also be varied.

This can act as a very simple and potentially powerful way of imparting joint resistance which could be used in resistive control systems for wearers with pathologic gait, although the method would not be able to provide actuation as it is simply a brake.

### 3.5.2 Summary

While compliant actuators are not always passive, they can be effective ways of reducing power usage of exoskeleton designs, such as through energy recuperation through springs. To analyse each of the several methods presented, elastomers and shape-memory materials seem to be limited in the amount of force they can provide, and as such would likely not be very useful for driving a full exoskeleton, rather than the often-partial assistive devices they have been seen in. Elastic belts show a similar usage pattern to cables with the same limitations of not being able to provide a pushing force, only pulling unless two were used in a pulley system.

As such it is likely that springs offer the best benefits for a low-cost system, with standard springs providing both pushing and pulling forces proportional to their compression and extension as long as they are not deformed elastically. Unfortunately none of the papers reviewed gave useful prices of springs or other reliable costs of other compliant actuator methods, however from external research, off the shelf springs of similar spring constants and sizes, for example in [149], a paper that makes use of a SODEMANN compression spring with a resting length of 0.044 m, range of 0.0185 m [150] amongst other components, a price range of ~£4-£6 is found for a single spring although this is quite a small spring, despite this, as even unreasonably sized springs of over a metre generated on the same site costed ~£150, which is less expensive than many other actuators, the cost of a reasonably sized spring would therefore be a negligible expense within the total cost of an exoskeleton's construction.

Compliant Materials are unlikely to see use as major actuators in exoskeletons due to the minimal amounts of force they can produce on their own, but may be useful for smaller, assistive or rehabilitative devices due to being inexpensive and having a low size profile, or alongside active actuator types.

In summary, springs seem to be excellent additions to a low-cost implementation, although are of limited outside of small scales unless paired with other actuators, such as in series elastic actuator configurations.

## 4 Discussion

This discussion will attempt to build theoretical exoskeleton actuator implementations for all actuator types based on available information, then compare the overall costs, weights, power usage, and effectiveness against each other as displayed in Table 10. This may provide useful quantitative analysis of various actuator implementations. For actuator types where less information was available such as hydraulic cylinders, an effort has been made to find some examples with available characteristics. These implementations will consist of

**Table 10** Actuator Type Characteristic and Cost Breakdown

Actuator Type	Component	Characteristics				Characteristics Total								
		Power (W)	Weight (g)	Force (N or Nm)	Cost (£)	Power (W)	Weight (g)	Force (N or Nm)	Cost (£)					
Rotary Electric Motor	Averaged Motor	150 W	415 g	0.32 Nm	£375	160 W	1165 g	48Nm ~ 130 N <sup>4</sup>	£1005					
	Averaged Encoder	0.25 W	50 g	-	£80									
	Averaged Gear Set	-	400 g <sup>1</sup>	150:1	£300 <sup>1</sup>									
	Averaged Driver <sup>2</sup>	+5%	300 g	-	£250									
Rotary Electric Motor+Ball Screw	Averaged Motor	150 W	415 g	0.32 Nm	£375	160 W	1665 g	~ 500 N	£1125					
	Ball Screw	-	900 g	4 mm lead	£370									
	Averaged Encoder	0.25 W	50 g	-	£80									
	Averaged Driver <sup>2</sup>	+5%	300 g	-	£250									
Linear Electric Motor	Averaged Linear Motor	200 W	1000 g*	60 N	£700*	210 W	1350 g	60 N	£1030					
	Averaged Encoder	0.25 W	50 g	-	£80									
	Averaged Driver <sup>2</sup>	+5%	300 g	-	£250									
Hydraulic Cylinder	Averaged Cylinder	-	600 g*	1800 N	£40?	370 W	3600 g+2000 g	1800 N	£1565					
	Estimated Valves/Solenoids <sup>2</sup>	5 W	500 g	-	£150*									
	Estimated Pump Motor <sup>2</sup>	350 W	1000 g	0.8 Nm	£500									
	Av. Pump Motor Encoder <sup>2</sup>	0.25 W	50 g	-	£80									
	Est. Pump Motor Driver <sup>2</sup>	+5%	770 g*	-	£725*									
	Estimated Piping <sup>2</sup>	-	200 g*	-	£20									
	Averaged Fluid Container <sup>2</sup>	-	500 g	-	£30 <sup>3</sup>									
	Estimated Fluid <sup>2</sup>	-	2000 g	-	£20									
	Pneumatic Cylinder	Estimated Cylinder	-	750 g*	1800 N					£150	1105 W	2070 g + 27 kg <sup>5</sup>	1800 N	£765
		Estimated Valves/Solenoids <sup>2</sup>	5 W	120 g	-					£100				
Estimated Piping <sup>2</sup>		-	150 g*	-	£15 *									
Estimated Gas Container <sup>2</sup>		-	1000 g	-	£150									
Estimated Compressor <sup>2</sup>		1 kW	27,000 g <sup>5</sup>	-	£350									

**Table 10** (continued)

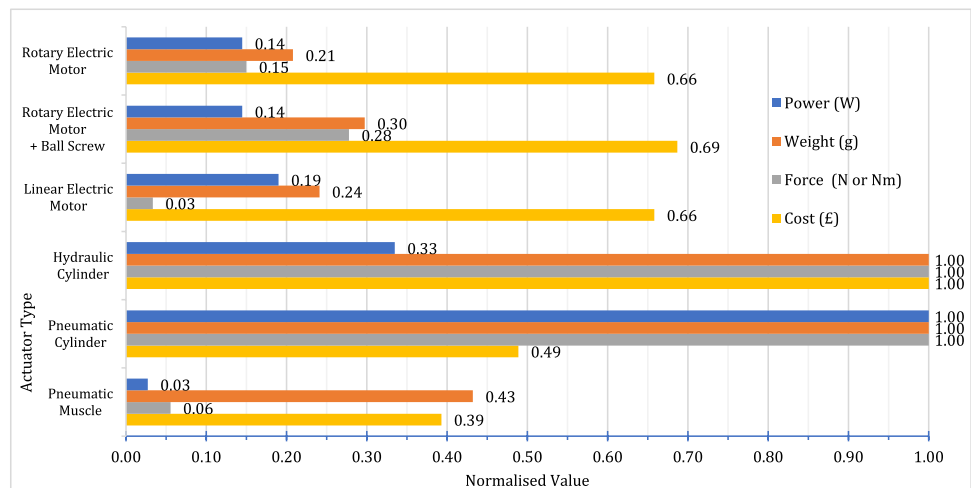
Actuator Type	Component	Characteristics				Characteristics Total			
		Power (W)	Weight (g)	Force (N or Nm)	Cost (£)	Power (W)	Weight (g)	Force (N or Nm)	Cost (£)
Pneumatic Muscle	Est. Fluidic/Inflatable Muscle <sup>1</sup>	-	200 g* <sup>1</sup>	100 N* <sup>1</sup>	£100* <sup>1</sup>	35 W	2470 g	100 N*	£615
	Estimated Valves/Solenoids <sup>2</sup>	5 W	120 g	-	£100				
	Estimated Piping <sup>2</sup>	-	150 g*	-	£15*				
	Estimated Gas Container <sup>2</sup>	-	1000 g	-	£150				
	Estimated Compressor <sup>2</sup>	30 W <sup>1</sup>	1000 g	-	£250				

<sup>1</sup> Values can range very considerably, this value is a middle ground, in practice, it may either be much more or much less than this.  
<sup>2</sup> This example assumes one of each component is purchased, meaning if multiple actuators are needed, the ratio of this component to other components may not be consistent. This may be because only one is required for the entire exoskeleton, or that the component can be expanded.  
<sup>3</sup> This is an estimate to the price of a 3L unpressurised tank as seen in [65, p. 10], a pressurised tank would be both heavier and more expensive.  
<sup>4</sup> For the purposes of comparing this torque value to the linear force values of the other actuators, it has been assumed that the motor is rotating a 20 cm shaft, with a force reading taken perpendicularly from its end, as this is a rough estimate to the length to the CoM of an average adult's upper leg.  
<sup>5</sup> Pneumatic Compressors capable of providing enough pressure to power cylinders seem to be too large to fit on the exoskeleton, therefore their weight would not count towards it, however their presence should still be considered. As such, for the purpose of scoring, pneumatic cylinders will have a normalised weight of 1.  
 \* This information is a "Best Guess" based on limited source components, in some cases as little as one.

the actuator itself, in addition to any peripherals it is stated to require. Averaged characteristics are averages of several components of a similar type (such as electric servo motors) while estimated are only of a small (3 or less) number of components. It is expected than in reality, actuator costs will vary wildly depending on specifications, availability, actuated joint target, and many other factors beyond the scope of this paper.

While Cables and Springs can both be used alongside other actuators or on their own, for the purpose of simplicity they have been paired with Rotary Electric Motors to see the effect they may have on the overall cost of the system, other compliant materials such as elastomers, as well as magnetic brakes offer too different of an actuation method to be effectively comparable to the current list. Figure 9 shows

**Fig. 9** Normalised Actuator Characteristics, note that for Power, Weight, and Cost higher values are worse, whereas for Force, lower values are worse



normalised values of actuator Power usage, weight, force output and costs

Rotary Electric Motors average out to be the lightest of the actuator types, with all electric motor types benefiting from not requiring any sort of fluid that must be contained and used for force application which is the primary source of weight for pneumatic and hydraulic actuators. This comes with the downside of a potentially high cost, especially due to the varying expense of gearing. Rotary motors with ball screws would not have to deal with as expensive gearing due to a higher reliance on high RPM to rotate the ball-screw, the less expensive gearing seems to counter most of the extra cost of the ball screw itself. The more numerous implementations of a motor and ball screw in place of traditional linear motors may be due to a superior force and lower weight and power usage. Hydraulic is the worst in all categories with the exception of force, which while on average tied with pneumatic cylinders can be considered superior due to a higher precision in application. However due to a high-power usage, weight, and cost it struggles to offer much relevance outside of industrial exoskeleton technologies. While Pneumatic Cylinders average out to be both low-power and low-cost, the compressor however is a divisive component as it is debatable as to how large of a gas tank would be needed to allow an exoskeleton to function for several hours without refill if there were no compressor, with a compressor the power and weight costs of the system would make it infeasible for every day usage. In all examples within the literature, this component is external, which would be infeasible for an exoskeleton seeing actual usage. The only benefit is that there would only need to be one of this component that would then power the rest of the system. Other than this, pneumatic systems may find some use in softer applications which may be able to use a lower power compressor for lower pressures. The normalised values displayed in Fig. 9 in addition to the Force to Weight Ratio, Impact, and Precision (described in Table 11). These will further rank the actuator types in a quantitative manner, with each being weighted according to different approaches. This is a similar albeit simpler financial analysis to what is seen in [151], which this paper took some inspiration from.

Impact describes the effect the exoskeleton has on the surrounding environment, such as from spillages, noise, or repairs. Precision describes how well the actuator can handle

precision movements. The values in brackets are the arbitrary normalised values assigned to them, as actual values do not appear to be readily available it was deemed impractical to find actual values.

The weights within Table 12 are defined semi-arbitrarily based on the perceived priorities of different exoskeleton types and as demonstration for quantitative analysis. The Equal Weights Approach exists as an unbiased control value to provide weights with no special priorities, in a sense showing how well rounded an actuator type may be.

The Industrial Augmentative Exoskeleton Approach prioritises high power to weight ratios and force, sacrificing precision and power usage to achieve this, as the exoskeleton is only required to follow the already healthy user and reduce strain, allowing for bulkier designs and higher power usage to support stronger actuation.

The Rehabilitative Exoskeleton Approach aims to aid a user capable of some ambulation to improve their gait pattern, it is therefore important that the exoskeleton does not detract from movement through imprecise movement or heavy weight, additionally as this device should be used in more home environments, it must be more power efficient and less impactful on the wider environment as to avoid disruption. It does not however require high force as the user is still capable of most of the walking motion themselves.

The Assistive Exoskeleton aims to provide walking functionality to those that would not be able to walk otherwise, and to therefore assist in the walking process. As with rehabilitative exoskeletons it therefore requires high precision, although its weight is less of a concern as the user's gait does not contribute heavily to the walking process. Instead, the system requires stronger actuators in order to move for them. Due to its specialized nature, this exoskeleton does not need to reduce costs as much.

The Low-Cost Approach is the focus of this paper and seeks to provide an alternative to the Rehabilitative Exoskeleton Approach that focuses on reducing financial cost by removing the need for high precision actuators, and reducing power usage through using the active elements of the actuator as little as possible.

Other approaches could also be designed to focus on whatever exoskeleton aspects would be desired by the user, for example rather than focusing on a type of exoskeleton it could instead focus on an exoskeleton purpose, e.g. a sit-to-stand exoskeleton would weight force-to-weight ratio highly, but may weight power usage and precision low as

**Table 11** Impact and Precision of Actuator Types

	Rotary Electric Motors	Rotary Electric Motors + Ball Screws	Linear Electric Motors	Hydraulic Cylinders	Pneumatic Cylinders	Pneumatic Muscles
Impact	Low (1)	Low (1)	Low (1)	High (0.5)	V. High (0.35)	Medium (0.75)
Precision	High (1)	High (1)	High (1)	High (1)	Medium (0.75)	Low (0.5)

**Table 12** Weights of Approach Criteria

	Power Usage	Actuator Weight	Actuator Force	Actuator Cost	F/W Ratio	Impact Reduction	Precision
Equal-Weights Approach	0.142857	0.142857	0.142857	0.142857	0.142857	0.142857	0.142857
Industrial Augmentative Exoskeleton Approach	0.1	0.125	0.2	0.125	0.225	0.125	0.1
Rehabilitative Exoskeleton Approach	0.15	0.175	0.1	0.125	0.15	0.15	0.15
Assistive Exoskeleton Approach	0.15	0.125	0.15	0.1	0.15	0.15	0.175
Low-Cost Approach	0.175	0.15	0.125	0.2	0.15	0.15	0.05

the exoskeleton is designed to assist in occasional but intense generalised movements as opposed to continual minor adjustments.

Table 13 contains the normalised results of the data from Tables 10 and 11 for the different approaches described in Table 12. For this calculation, the Power, Weight, and Cost were normalised to the lowest value rather than the highest as displayed in Fig. 9, this was so that the highest values were always “better”, as lower power usage, weight, and cost are more desirable.

The result of the table show that Rotary Electric Motors are, on average the most effective actuator, which is consistent with it being the most commonly used, either without or in combination with ball screws. Rotary Electric Motors in combination with ball screws saw higher scores than standard Linear Electric Motors which may also be why they are so comparatively uncommon as any time where a linear actuator would be applicable, the rotary electric motor + ball screw has a higher score. Meanwhile, there is a considerable gap in score between electric motors and Hydraulic and Pneumatic Actuators. For Hydraulic and Pneumatic Cylinders, this is as a result of their very high weights, which plummet their overall score by significant margins, they did however see prominence in Industrial Exoskeleton Approaches, being the highest scoring methods, although while pneumatic was marginally higher, it assumes a method of easily carrying the separate compressor that would be required for extended function. If this method was not present, hydraulic would be superior due to being more easily self-contained. Pneumatic muscles meanwhile saw little significance in most categories due to a weight score crippling otherwise promising low power usage and costs.

These values were made with only a single actuator in mind, however as several components would only need to be purchased once such as motor drivers, or hydraulic pumps, or would not scale directly in some capacity if multiple actuators were needed such as a solenoid which can have multiple ports in one block, or fluid piping which would only need to connect between the new actuator and pump, components that may only need to be counted once or at a reduced rate are referenced in Table 10, under “2”.

Furthermore, it is unlikely all actuators will be functioning simultaneously, reducing power usage for electric motors and fluid throughput requirements for hydraulic and pneumatic implementations. This becomes difficult to calculate, and as such could be a topic for future study. It can however be speculated that Electric Motor types would suffer more as the vast majority of their components are needed for each new actuator, with only the controller being able to be used across multiple. Hydraulic and Pneumatic actuators meanwhile could benefit from a single centralised pump and cheaper individual cylinders or muscles for each actuator, translating into reduced cost, although not necessarily reduced weight when compared to electric motors.

When considering the implementation of compliant elements or transmission systems such as springs, there will be a minor increase in weight from additional hardware, and a potential loss of precision due to uncontrolled movement from these elements. Each presents different, less quantifiable benefits as outlined in their relevant sections, cables allowing for the relocation of actuators to more favorable positions, for example, moving actuators from locations on the leg to a backpack worn by the user, therefore reducing the effect of inertia on walking. For compliant elements a level of feedback prevention is provided as compliant elements can absorb impacts as well as store energy.

Series Elastic actuators and other similar implementations are the most common implementation involving multiple different types of actuator being used within the same exoskeleton, often taking the form of a spring and rotary electric motor, theoretically a similar design could be made with multiple types of active actuator. A simple example of such an implementation can be imagined for an industrial exoskeleton. It would make use of hydraulic or pneumatic actuator for joints that would experience high force loads, such as hip, knee, and ankle flexion/extension, however for degrees of freedom that may see less load such as ankle abduction/adduction or hip rotation, geared electric motors could be used due to their smaller volume. This could reduce complexity and weight due to the need for less hydraulic fluid capacity and cabling. As seen in Table 13, both rotary electric motors and hydraulic cylinders score highly for an

**Table 13** Normalised Actuator Scores for Different Approaches

	Rotary Electric Motors	Rotary Electric Motors + Ball Screws	Linear Electric Motors	Hydraulic Cylinders	Pneumatic Cylinders	Pneumatic Muscles
Equal-Weights Approach	0.9966	<b>1.0000</b>	0.8080	0.8953	0.8861	0.8321
Industrial Augmentative Exoskeleton Approach	0.9445	0.9934	0.6829	0.9967	<b>1.0000</b>	0.6884
Rehabilitative Exoskeleton Approach	<b>1.0000</b>	0.9844	0.8149	0.8171	0.7932	0.8114
Assistive Exoskeleton Approach	0.9836	<b>1.0000</b>	0.7942	0.9233	0.8744	0.7851
Low-Cost Approach	<b>1.0000</b>	0.9967	0.7928	0.8329	0.8929	0.9654

Industrial Augmentative Exoskeleton Approach, using them together could be analysed quantitatively by averaging the two scores ( $\frac{0.9967 + 0.9445}{2} = 0.9706$ ).

One final aspect that has not been discussed within the paper is that the financial costs of the actuators and their respective peripheral components only encompasses the initial investment of purchasing them. Another similar point considered of near-equal significance by stakeholders of exoskeleton technologies is the cost of maintaining and repairing such components and the exoskeleton as a whole [159, p. 5]. Such maintenance costs would vary dependant on factors such as the reliability of the components, the intensity, frequency, requirements of the tasks they perform, and the environment that the exoskeleton functions in. Per-actuator costs are difficult to calculate exactly, although there are some examples within literature of “Maintenance Contracts” for the total cost of exoskeleton servicing per year, in [152] a maintenance contract of an exoskeleton was estimated at ~£7,400 (\$10,000) per year, with a lifespan of 5 years and initial device cost of ~£110,000 (\$150,000). In this instance, assuming that after the 5-year lifespan the exoskeleton would need replacement, maintenance represented  $\frac{1}{4}$  of the total cost of the exoskeleton, although it is important to note not all of the remaining initial device cost would be as a result of the construction of the exoskeleton and its components. It is also likely that initial costs would decrease at a more rapid rate than maintenance costs with the development of the exoskeleton industry.

To place an estimate for individual component’s lifetimes [153] predicts an electric motor to function for ~20,000 h of runtime in ideal conditions, which is in line with the estimates given by Maxon for their motors [154], although they also state 1000–3000 h is more expected in average conditions. Pneumatic Cylinders meanwhile have been estimated to last up to 10’s of millions of cycles [155], which is somewhat in line with a prediction made by the Bimba Manufacturing Company predicting its cylinders could function for a total travel distance of 3,000 miles [156], if a cycle equated to ~40 cm, this would equate

to ~12 million cycles. While it does not seem unreasonable to assume hydraulic cylinder and pneumatic cylinder data would be similar, both are likely to suffer in terms of lifetime as a result of other peripheral components, notably leaks in piping as well as wear and tear in pumps and compressors which will cause gradual degradation of actuator quality, necessitating regular replacement or maintenance, as well as cleaning up any mess they make due to leaks, which an end user may consider to be worse than the maintenance itself.

As a summary, quantitative analysis on actuator characteristics reveals rotary electric motors score well for the most types of exoskeleton approaches, which is in line with them being the most common actuator type within the reviewed dataset. How these scores would be affected by considering multiple actuators however becomes difficult to calculate.

#### 4.1 Conceptual Low-Cost design of a Lower-limb Exoskeleton

Based off of the findings of this paper, Rotary Electric Motors seem to be an effective low-cost actuator, when looking to further optimise for a low-cost implementation, choosing rotary electric motors with low power usage and low financial cost would be ideal, such as an off-the-shelf hobby motor. Such actuators may not be capable of as high speeds, small sizes, high precision, and low latency when compared to those seen within this paper, therefore a low-cost implementation should attempt to resolve or otherwise nullify these issues.

A conceptual knee actuator proposal shown in Fig. 10 may make use of an off-the-shelf actuator that does not directly control the movement of the joint it is a part of actuating. A compliant spring is responsible for actuation, having effectively zero latency and being capable of absorbing with sudden movements. The motor meanwhile is used to vary the length of the spring, which results in a varying force output, this does not need to be either precise or low latency, instead only needing sufficient torque to continue rotating the spring even while under strain.



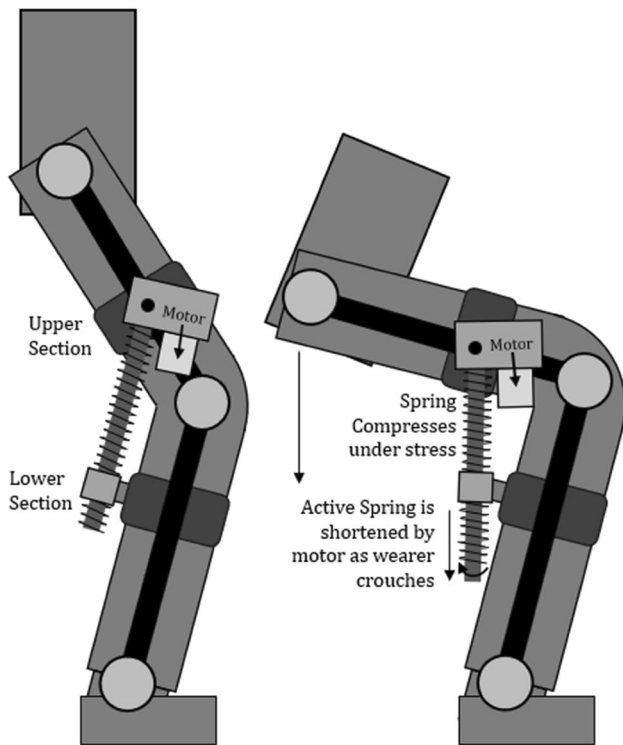


Fig. 10 Conceptual Knee actuator proposal

The length of the spring is varied by rotating it like a screw jack through the lower section of the structure, rotating the spring in one direction “activates” more of the spring increasing the force it applies, while a shorter active spring does the inverse. This method is similar in nature to the rotary motor and ball screw, with the ball screw replaced with a less expensive and lighter spring.

From Preliminary design work done on this subject as part of wider study, the two parts of the exoskeleton relevant

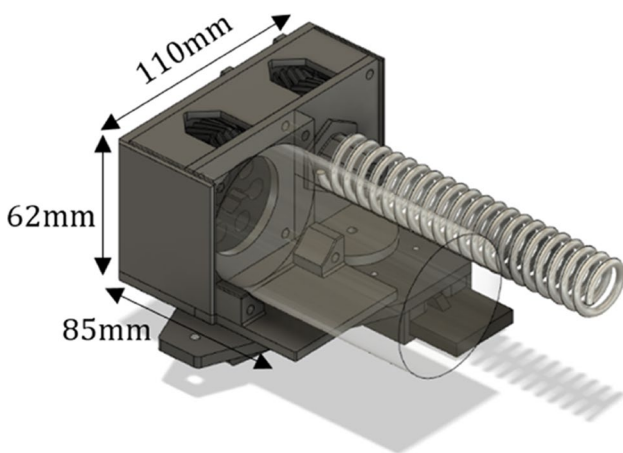


Fig. 11 Conceptual Knee Design—Upper Section (Note – Spring not to scale)

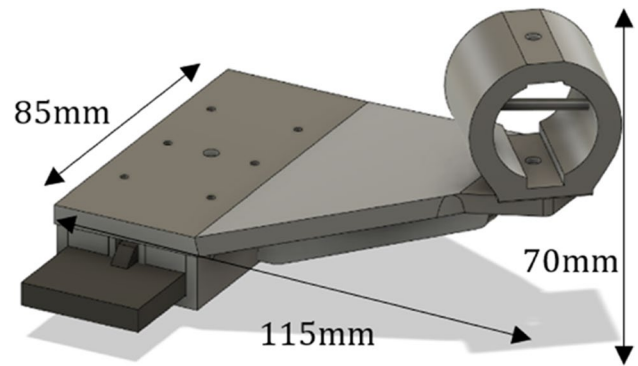


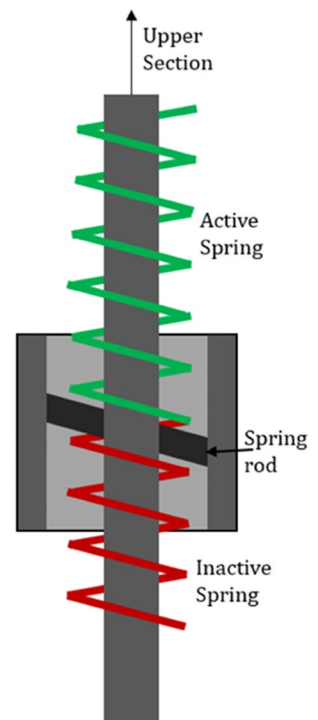
Fig. 12 Conceptual Knee Design—Lower Section

to actuation are named the upper and lower sections. The upper section (Fig. 11) is connected to the upper leg via a rotatable resolute joint and contains a brushless DC servo motor connected by two gears to a Stainless steel spring. The spring has a diameter of 24 mm, a length of 300 mm, and a pitch of 9.5 mm.

The Lower section (Fig. 12) consists extends out from the leg and raises up to be in line with the upper section, the spring slots through a tube connected by another resolute joint. Within this tube is a rod that the spring rests and pushes on.

When the spring is rotated by the servo motor, it slides past the lower-section spring rod. As shown in Fig. 13, any part of the spring that is past the rod is “inactive”, and will not be compressed if strain is placed upon it by the upper leg section. Effectively rotating the servo motor increases and decreases

Fig. 13 Cross Section of Conceptual Knee Design Lower Section



the spring length and so the force it can apply. A slotted tube runs down the centre of the spring to prevent it from bending, which would reduce applied force.

Future study will expand on this design.

## 5 Conclusion

This review discusses a variety of actuator implementations used in exoskeletons and has attempted to analyse whether they would be suitable in exoskeletons designed for low-cost implementations. While this review focuses on lower-limb exoskeletons, the actuators here are similar to those seen in other exoskeleton designs for the upper body, and as such its conclusions could be used there as well.

This paper is biased towards the concept of an “intermediary” or “home” exoskeleton, a device that can be worn by a patient that is not necessarily capable of fully rehabilitating any pathologic gait issues, but can, at a bare minimum, prevent further degradation for issues such as crouch gait which if left untreated would lead to long-term harm to leg musculature and permanent walking issues. Such an exoskeleton would need to be wearable during everyday life, and therefore should have minimal impact on the wearer (low weight cost), be capable of functioning for long periods of time (low power cost) and be practically affordable (low financial cost) while still capable of fulfilling the purpose of preventing or reducing gait degradation (sufficient effectiveness). It has been judged by the author that the actuator is the key component whose state affects the cost of many other components and has therefore been the focus of this paper. This judgement has been made based off of the impact the actuator has upon all other components.

For powered actuators, the requirements of hydraulics and pneumatics for bulky external peripherals lead to a high weight cost and higher complexity, more peripherals, especially ones that have to work with fluids, will lead to more wear and tear on a device that would benefit from being simpler to use. The biggest flaw of many rotary electric motors meanwhile is their price will not necessarily scale as well when considering multiple actuators, as many of their components are needed for each new actuator on an exoskeleton, especially due to the commonly seen usage of expensive, low latency, high precision, high torque motors in combination with their peripherals. A solution to this may be to find a way to use less advanced off-the-shelf actuators, implemented in such a way where their inferiorities are made redundant, for example, by combining them with compliant actuators.

In summary, this paper proposes low-cost actuator implementations for simple and reliable exoskeletons that can potentially reduce gait degradation in patients such that they can attend more advanced rehabilitation sessions without losing progress, or, for assistive cases, have access to intelligent assistive exoskeletons without serious financial investment.

Regardless, both could lead to a faster and more efficient improvement the patient’s walking ability.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s10846-022-01695-0>.

**Author’s Contributions** Tom Slucock: Research and Manuscript Compilation.

## Declarations

**Conflicts of Interest** The Author Declares no Conflicts of Interest.

**Ethics Approval** The Author has read and approved this manuscript.

**Consent to Participate** Not Applicable.

**Consent for Publication** The Author has agreed to publish this manuscript.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

1. Yagn, N: "Apparatus for Walking, Running, Jumping". United States of America Patent 420,179, (1890)
2. Vukobratovic, M., Hristic, D., Stojiljkovic, Z.: Development of active anthropomorphic exoskeletons. *Med. Biol. Eng.* **12**(1), 66–80 (1974)
3. Specialty Materials Handling Products Operation General Electric Company, Hardiman I Prototype Project. (1968)
4. Zoss, A., Kazerooni, H. Chu, A.: "On the Mechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)," in *IEEE/RSJ International Conference on Intelligent Robotics*, pp. 3465–3472. (2005)
5. Sankai, Y.: "HAL: Hybrid Assistive Limb based on Cybernics," in *Springer Tracts in Advanced Robotics*, pp. 25–34. (2007)
6. Stoye, G., Zaranko, B.: "UK Health Spending," *The Institute for Fiscal Studies*. (2018)
7. Jones, A.: Interviewee, Ectron EksoNR cost. [Interview]. (2021)
8. Centers for Medicare & Medicaid Services: "National Health Expenditures 2019 Highlights," *Centers for Medicare and Medicaid Services*. (2019)
9. Gonzalez, A., Garcia, L., Kilby, J., McNair, P.: Robotic Devices for Paediatric rehabilitation: a review of design features. *Biomed. Eng. Online* **20**(89), 1–33 (2021)
10. Slucock, T.: "A Systematic Review of Lower-Cost Actuator Implementations for Lower-Limb Exoskeletons - Addendums". [Online]. Available: <https://drive.google.com/drive/folders/>

- 1VbrkzbnWZbbhKiqB3QxtUqZAcasgIjNjX?usp=sharing. (2021). Accessed 17 November 2021
11. Neuhaus, P. D., Noorden, J. H., Craig, T. J., Torres T., Kirschbaum, J., Pratt, J. E.: "Design and Evaluation of Mina a Robotic Orthosis for Paraplegics," in IEEE International Conference of Rehabilitation Robotics. (2011)
  12. Moog: "BN34 Specifications," [Online]. Available: <https://www.moog.com/content/dam/moog/literature/MCG/BN34-BrushlessDCMotorsDtS.pdf>. Accessed 22 November 2021
  13. Brundu, A.: Interviewee, Moog BN34–25EU-02 Servo Motor Costs. [Interview]. (2021)
  14. Marian, P., Danut, I., Nirvana, P., Dorin, P.: "Engineered Devices to Support Stroke Rehabilitation," in 19th International Conference on Control Systems and Computer Science, pp. 289–295. (2013)
  15. Omron: "SGDH Sigma-II servo Drive," [Online]. Available: <http://www.farnell.com/datasheets/2923102.pdf>. Accessed 2021 November 21
  16. Omron: "Sigma-II rotary servo motors," [Online]. Available: [https://assets.omron.eu/downloads/datasheet/en/v4/i47e\\_sgm\\_h-sigma-ii\\_rotary\\_servo\\_motors\\_datasheet\\_en.pdf](https://assets.omron.eu/downloads/datasheet/en/v4/i47e_sgm_h-sigma-ii_rotary_servo_motors_datasheet_en.pdf). Accessed 21 November 2021
  17. Lerner, Z.F., Gasparri, G.M., Bair, M.O., Lawson, J.L., Luque, J., Harvey, T.A., Lerner, A.T.: An Untethered Ankle Exoskeleton Improves Walking Economy in a Pilot Study of Individuals With Cerebral Palsy. *IEEE Trans. Neural Syst. Rehabil. Eng.* **26**(10), 1985–1993 (2018)
  18. Maxon: "EC-4pole 22 Ø22 mm, brushless, 90 Watt | High Power," Maxon, [Online]. Available: <https://www.maxongroup.com/maxon/view/product/323218>. Accessed 21 November 2021
  19. Baud, R., Ortlieb, A., Oliver, J., Bouri, M.: "HiBSO hip exoskeleton: Toward a wearable and autonomous design," in MESROB, pp. 185–195. (2016)
  20. Maxon: "RE 30 Ø30 mm, Graphite Brushes, 60 Watt," [Online]. Available: [https://www.maxongroup.com/medias/sys\\_master/root/8881622155294/EN-21-148.pdf](https://www.maxongroup.com/medias/sys_master/root/8881622155294/EN-21-148.pdf). Accessed 21 November 2021
  21. Maxon: "Screw Drive GP 22 S Ø22 mm, Metric spindle, M6 x 1," [Online]. Available: <https://www.maxongroup.com/maxon/view/product/363826>. Accessed 08 December 2021
  22. Vouga, T., Baud, R., Fasola, J., Bouri, M., Bleuler, H.: "TWIICE - A Lightweight Lower-Limb Exoskeleton for Complete Paraplegics," in IEEE International Conference on Rehabilitation Robotics, pp. 1639–1645. (2017)
  23. Sonceboz: "Brushless - DC Motors 5612," [Online]. Available: <https://pdf.directindustry.com/pdf/sonceboz/brushless-dc-motors-5612/14206-588571.html>. Accessed 22 November 2021
  24. Yang, W., Yang, C.-J., Wei, Q.-X.: "Design of an Anthropomorphic Lower Extremity Exoskeleton with Compatible Joints," in IEEE International Conference on Robotics and Biomimetics, pp. 1374–1379. (2014)
  25. Maxon: "EC 90 flat Ø90 mm, brushless, 90 Watt, with Hall sensors," [Online]. Available: <https://www.maxongroup.com/maxon/view/product/323772>. Accessed 21 November 2021
  26. Zhang, T., Tran, M., Huang, H.: Design and Experimental Verification of Hip Exoskeleton With Balance Capacities for Walking Assistance. *IEEE/ASME Trans. Mechatron.* **23**(1), 274–285 (2018)
  27. Minhyung, L., Kim, J., Hyung, S., Lee, J., Seo, K., Park, Y.J., Cho, J., Choi, B.-K., Shim, Y., Choi, H.: A Compact Ankle Exoskeleton With a Multiaxis Parallel Linkage Mechanism. *IEEE/ASME Trans. Mechatron.* **26**(1), 191–202 (2021)
  28. Maxon: "DCX 32 L Ø32 mm, Graphite Brushes, ball bearings," [Online]. Available: <https://www.maxongroup.com/maxon/view/product/motor/dcmotor/DCX/DCX32/DCX32L01GBKL470>. Accessed 22 November 2021
  29. Taylor, G.: Interviewee, ABSSAC SG0504 Costs. [Interview]. (2021)
  30. Walsh, C. J., Paluska, D., Pasch, K., Grand, W., Valiente, A., Herr, H.: "Development of a lightweight, underactuated exoskeleton for load-carrying augmentation," in IEEE International Conference on Robotics and Automation, pp. 3485–3491 (2006)
  31. Maxon: "RE 40 Ø40 mm, Graphite Brushes, 150 Watt," [Online]. Available: <https://www.maxongroup.com/maxon/view/product/motor/dcmotor/re/re40/148866>. Accessed 21 November 2021
  32. Colombo, G., Jorg, M., Schrier, R., Dietz, V.: Treadmill training of paraplegic patients using a robotic orthosis. *J. Rehabil. Res. Dev.* **37**(6), 693–700 (2000)
  33. Michimizos, K. P., Krebs, H. I.: "Assist-as-needed in Lower Extremity Robotic Therapy for Children with Cerebral Palsy," in IEEE International Conference on Biomedical Robotics and Biomechanics, pp. 1081–1086 (2012)
  34. "EC-4pole 22 Ø22 mm, brushless, 90 Watt | High Power," [Online]. Available: <https://www.maxongroup.com/maxon/view/product/327739>. Accessed 21 November 2021
  35. Kardan, I., Akbarzadeh, A.: Robust output feedback assistive control of a compliantly actuated knee exoskeleton. *Robot. Auton. Syst.* **98**, 15–29 (2017)
  36. Ortlieb, A., Bouri, M., Baud, R., Bleuler, H.: "An Assistive Lower Limb Exoskeleton for People with Neurological Gait Disorders," in International Conference on Rehabilitation Robotics, pp. 441–446 (2017)
  37. Maxon: "Planetary Gearhead GP 32 HP Ø32 mm, 4.0 - 8.0 Nm, Metal Version, High Power | High Power," [Online]. Available: <https://www.maxongroup.com/maxon/view/product/326671>. Accessed 22 November 2021
  38. Washabaugh, E.P., Claflin, E.S., Gillespie, R.B., Krishnan, C.: A Novel Application of Eddy Current Braking for Functional Strength Training During Gait. *Ann. Biomed. Eng.* **44**(9), 2760–2773 (2016)
  39. The Robot Marketplace: "Banebots Gearboxes," [Online]. Available: <http://www.robotcombat.com/products/0-P60K-55-0004.html>. Accessed 2 December 2021
  40. Anonymous-Company: Interviewee, Strain Wave Gear Example Price. [Interview]. (2021)
  41. He, Y., Li, N., Wang, C., Xia, L.-Q., Yong, X., Wu, X.-Y.: Development of a novel autonomous lower extremity exoskeleton robot for walking assistance. *Front. Inf. Technol. Electron. Eng.* **30**, 318–329 (2019)
  42. Felix, P., Figueiredo, J., Santos, C. P., Moreno, J. C.: "Powered Knee Orthosis for Human Gait Rehabilitation: First Advances," in IEEE 5th Portuguese Meeting on Bioengineering, pp. 1–4. (2017)
  43. Park, J.-H., Lee, J.-S., Shin, J.-S., Cho, B.-K.: "Design of a Lower Limb Exoskeleton Including Roll Actuation to Assist Walking and Standing Up," in IEEE-RAS 15th International Conference on Humanoid Robotics (Humanoids), pp. 359–364. (2015)
  44. Maxon: "Encoder ENC 16 RIO, 16384 counts per turn, 3-channel, with RS 422 line driver," [Online]. Available: <https://www.maxongroup.com/maxon/view/product/575829>. Accessed 2 December 2021
  45. RLS: "RMB28 Rotary Magnetic Encoder Module," [Online]. Available: <https://www.rls.si/eng/rmb28-rotary-magnetic-module?partNumbers=RMB28IC10BS11>. Accessed 2 December 2021
  46. Mouser Electronics: "HEDL-5640#A13," [Online]. Available: <https://www.mouser.co.uk/ProductDetail/Broadcom-Limited/HEDL-5640A13?qs=sGAEpiMZZMuGN2ig0xo6GwpTtpKC14je>. Accessed 2 December 2021
  47. Emken, J.L., Wynne, J.H., Harkema, S.J., Reinkensmeyer, D.J.: A Robotic Device for Manipulating Human Stepping. *IEEE Trans. Rob.* **22**(1), 185–189 (2006)

48. RS: "Models HSR-A and HSR-AM, Models HSR-LA and HSR-LAM," [Online]. Available: <https://docs.rs-online.com/1cbb/0900766b80f448f1.pdf>. Accessed 13 January 2022
49. Pietrusinski, M., Unluhisarcikli, O., Cajigas, I., Bonato, P.: "Design of Human - Machine Interface and Altering of Pelvic Obliquity with RGR Trainer," in IEEE International Conference on Rehabilitation Robotics, pp. 1–6. (2011)
50. KOMP-ACT: "KLM-40-0F4 KOMP-ACT LINEAR MOTOR," [Online]. Available: <https://komp-act.com/wp-content/uploads/2021/06/KLM-40-0F4.pdf>. Accessed 16 December 2021
51. Saito, Y., Kikuchi, H., Negoto, H., Oshima, T., Haneyoshi, T., Hatoyama-cho, I., Saitama, H.-G.: "Development of externally powered lower limb orthosis with bilateral-servo actuator," in 9th International Conference on Rehabilitation Robotics, pp. 394–399. (2005)
52. Zoss, A.B., Kazerooni, H., Chu, A.: Biomechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX). *IEEE/ASME Trans. Mechatron.* **11**(2), 128–138 (2006)
53. Kaminaga, H., Amari, T., Niwa, Y., Nakamura, Y.: "Development of knee power assist using backdrivable electro-hydrostatic actuator," in IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 5517–5524. (2010)
54. Kim, H.G., Lee, J.W., Jang, J., Park, S., HC: Design of an Exoskeleton with minimized energy consumption based on using elastic and dissipative elements. *Int. J. Control Autom Syst* **13**(2), 463–474 (2015)
55. Sun, M., Ouyang, X., Mattila, J., Yang, H., Hou, G.: One Novel Hydraulic Actuating System for the Lower-Body Exoskeleton. *Chin. J. Mech. Eng.* **34**(1), 1–10 (2021)
56. Staman, K., Vaele, A.J., van der Kooij, H.: Design, control and evaluation of the Electro-Hydrostatic Actuator, PREHydRA, for Gait Restoration Exoskeleton Technology. *IEEE Trans. Med. Robot. Bionics* **3**(1), 156–165 (2021)
57. Kollmorgen: "AKM Servo Motor Selection Guide," [Online]. Available: <https://cdn.kyklo.co/assets/W1siZiIsIjIwMjE-vMDMvMjE0MTIvNTUvMzcvNzY1Mjg2NGItNjIzNi00O-WFjLWlYyZmMGMGY0OTRmYmU3ZjZkL0t0vbGxtb3JnZW4IM-jAtJTIwQUtNjTIwc2VyaWVzJTlWLSUyMENhdGFsb2cMjAyMDE3LnBkZiJdXQ?sha=a34ad8186ed4c2fa>. Accessed 8 December 2021
58. Minuteman | Empire: "9/16" Heavy Duty, Double Acting, Clevis Mount, 6," [Online]. Available: <https://shop.maseas.com/9-16-heavy-duty-double-acting-clevis-mount-6-h9c-6d.html>. Accessed 8 December 2021
59. iAutomation: "AKM22C-BNBNC-00," [Online]. Available: <https://shop.i-automation.com/products/AKM22C-BNBNC-00>. Accessed 8 December 2021
60. Wang, B., Liang, Y., Xu, D., Wang, Z., Ji, J.: Design on Electro-hydraulic servo driving system with walking assisting control for lower limb exoskeleton robot. *Int J Advanced Robotic Systems* **18**(1), 1–17 (2021)
61. H. Wu, A. Kitagawa, H. Tsukagoshi and C. Liu, "Development of a Novel Pneumatic Power Assisted Lower Limb for Outdoor Walking by the Use of a Portable Pneumatic Power Source," in *16th IEEE International Conference on Control Applications*, pp. 1291–1296, 2007.
62. Fujikura Composites: "BF Cylinder," [Online]. Available: [https://www.fujikura-control.com/english/product\\_info/index.php/search?cell003=Air+Cylinders&cell004=BF+cylinder&label=1](https://www.fujikura-control.com/english/product_info/index.php/search?cell003=Air+Cylinders&cell004=BF+cylinder&label=1). Accessed 23 November 2021
63. Sato, M., Yagi, E.: "A Study on Power Assist Suit Using Pneumatic Actuators Based on Calculated Retaining Torques for Lift-Up Motion," in SICE Annual Conference, pp. 628–632. (2011)
64. RS: "RS PRO Pneumatic Profile Cylinder 32mm Bore, 200mm Stroke, CDEM Series, Double Acting," [Online]. Available: <https://uk.rs-online.com/web/p/pneumatic-piston-rod-cylinders/4802169>. Accessed 1 December 2021
65. Li, Y. D., Hsiao-Weksler, E. T.: "Gait Mode Recognition and Control for a Portable-Powered Ankle Foot Orthosis," in IEEE International Conference on Rehabilitation Robotics, pp. 1–8. (2013)
66. Parker: "Pneumatic Rotary Actuators," [Online]. Available: [https://www.parker.com/Literature/Pneumatics%20Division%20Europe/PDE-Documents/Cylinders/Parker\\_Pneumatic\\_PRO-PRN\\_Pneumatic\\_Rotary\\_Actuators\\_PDE2502TCUK.pdf](https://www.parker.com/Literature/Pneumatics%20Division%20Europe/PDE-Documents/Cylinders/Parker_Pneumatic_PRO-PRN_Pneumatic_Rotary_Actuators_PDE2502TCUK.pdf). Accessed 8 December 2021
67. Tidyco: "PRN30D-90-45," [Online]. Available: <https://tidyco.co.uk/store/parker-hannifin/parker-hannifin-detail.asp?ProductID=PRN30D-90-45>. Accessed 21 November 2021
68. Yamada, Y., Endo, G., Fukushima, E.F.: Pneumatic walking assistive device for use over long period. *Adv. Robot.* **28**(18), 1253–1264 (2014)
69. Zheng, H., Shen, T., Afsar, M. R., Kang, I., Young, A. J., Shen, X.: "A Semi-Wearable Robotic Device for Sit-to-Stand Assistance," in IEEE 16th International Conference on Rehabilitation Robotics, pp. 204–209. (2019)
70. Bimba: "Original Line® Air Cylinder," [Online]. Available: <https://www.bimba.com/en/detail/original-line-cylinder?rp=173.5-DPY>. Accessed 21 November 2021
71. Yamamoto, S., Miyoshi, T., Komeda, T., Hiramatsu, K., Nakazawa, K., Akai, M.: "Development of Pneumatic Gait Assist System," in IEEE/ICME International Conference on Complex Medical Engineering, pp. 1337–1340. (2007)
72. Chandrapal, M., Chen, X.: "Intelligent Active Assistive and Resistive Orthotic Device for Knee Rehabilitation," in IEEE International Conference on Control and Automation, pp. 1880–1885. (2009)
73. Park, Y.-L., Chen, B.-R., Young, D., Stirling, L., Wood, R. J., Goldfield, E., Nagpal, R.: "Bio-inspired Active Soft Orthotic Device for Ankle Foot Pathologies," in IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 4488–4495. (2011)
74. FESTO: "Fluidic muscle DMSP," [Online]. Available: [https://www.festo.com/media/pim/555/D15000100140555.PDF?siteUId=fox\\_gb&siteName=Festo+GB](https://www.festo.com/media/pim/555/D15000100140555.PDF?siteUId=fox_gb&siteName=Festo+GB). Accessed 16 December 2021
75. FESTO: "Fluidic muscle," [Online]. Available: <https://www.festo.com/gb/en/a/download-document/datasheet/541403/?CallID=QuickSearch>. Accessed 16 December 2021
76. Sasaki, D., Noritsugu, T., Takaiwa, M.: "Development of Pneumatic Lower Limb Power Assist Wear without Exoskeleton," in IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1239–1244. (2012)
77. Sasaki, D., Noritsugu, T., Takaiwa, M.: "Development of Pneumatic Lower Limb Power Assist Wear driven with Wearable Air Supply System," in IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 4440–4445. (2013)
78. Chung, J., Heimgartner, R., O'Neill, C. T., Phipps, N. S., Walsh, C. J.: "ExoBoot, a soft inflatable robotic boot to assist ankle during walking: Design, Characterization, and Preliminary Tests," in 7th IEEE International Conference on Biomedical Robotics and Biomechatronics, pp. 509–516. (2018)
79. Park, J., Choi, J., Kim, S.J., Seo, K.-H., Kim, J.: Design of an Inflatable Wrinkle Actuator With Fast Inflation/Deflation Responses for Wearable Suits. *IEEE Robot. Autom. Lett.* **5**(3), 3799–3805 (2020)
80. Mauer: "EMGR - EAS 90 L4," [Online]. Available: <https://www.motor-mauer.de/elektromotor-wechselstrom-lichtstrommotor-emgr-eas90l4-wechselstrommotor-einphasen-230-v-motor-shop-kaufen-1-1-kw-1500-min-1>. Accessed 14 December 2021

81. Thalman, C. M., Hertzell, T., Lee, H.: "Toward A Soft Robotic Ankle-Foot Orthosis (SR-AFO) Exosuit for Human Locomotion: Preliminary Results in Late Stance Plantarflexion Assistance," in 3rd IEEE International Conference on Soft Robotics, pp. 801–807 (2020)
82. PAR Group Ltd.: "TPU93 Thermoplastic Polyurethane - Orange BANCOLLAN, Technical Data Sheet," [Online]. Available: <https://www.par-group.co.uk/site-content/1/Docs/updates/1-rubber-and-polyurethane/1.26-tpu93-thermoplastic-polyurethane-orange-bancollan-tds.pdf>. Accessed 10 December 2021
83. Rockywoods: "200 DENIER COATED OXFORD NYLON FABRIC (SOLD PER YARD)," [Online]. Available: <https://www.rockywoods.com/200-Denier-Packcloth-Nylon-Fabric>. Accessed 10 December 2021
84. KOMP-ACT: "KDRV-1-MK-X-X Electronic Controller," [Online]. Available: <https://komp-act.com/wp-content/uploads/2021/06/KDRV-1-MK-X-X.pdf>. Accessed 16 December 2021
85. Chinchwad, Pimpri: Hydraulic Valves, Actuators, and Accessories.
86. iAutomation: "S20260-VTS," [Online]. Available: <https://shop.i-automation.com/products/S20260-VTS>. Accessed 8 December 2021
87. Adami, M., Seibel, A.: On-Board Pneumatic Pressure Generation Methods for Soft Robotics Applications. *Actuators* **8**(2), 1–35 (2019)
88. Hussain, S., Xie, S.Q., Jamwal, P.K., Parsons, J.: An Intrinsically Compliant Robotic Orthosis for Treadmill training. *Med. Eng. Phys.* **34**(10), 1448–1453 (2012)
89. Costa, N. R. S., Caldwell, D. G.: "Control of a Biomimetic "Soft-Actuated" Lower Body 10DOF Exoskeleton," in The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, pp. 495–501 (2006)
90. Johnson, D. C., Repperger, D. W., Thompson, G.: "Development of a Mobility Assist for the paralyzed, Amputee, and Spastic Patient," in Fifteenth Southern Biomedical Engineering Conference, pp. 67–70 (1996)
91. Gu, Y., Lv, Y., Ma, X., Lu, C.: "Lower-Limb Soft Orthotic Device for Gait Assistance," in 4th Information Technology and Mechatronics Engineering Conference, pp. 894–897. (2018)
92. Sasaki, D., Nortisugu, T., Takaiwa, M.: Development of High Contractile Pneumatic Artificial Rubber Muscle for Power Assist Device. *J. Robot. Mechatronics* **24**(1), 150–157 (2012)
93. MegaDepot: "STC 2S020-1/8A-3-D-V 2S020 Direct Acting 2 Way SS Solenoid Valve," [Online]. Available: <https://megadepot.com/product/stcvalve-2s020-1-8a-3-d-v-2s020-110vac-din-coil-1-8-npt-9mm-direct-acting-2-way-ss-solenoid-valve>. Accessed 19 December 2021
94. Wright, L. G. M. A. C. Kathy: Interviewee, *Humphrey Enquiry*. [Interview]. (2021)
95. ANSGear: "NINJA DURA PRO SLP CARBON FIBER AIR TANK - 68/4500 - BLACKOUT," [Online]. Available: [https://www.ansgear.com/Ninja\\_Dura\\_Pro\\_SLP\\_Carbon\\_Fiber\\_Air\\_Tank\\_68\\_4500\\_p/ninjatankpro-68slpdurablackout.htm](https://www.ansgear.com/Ninja_Dura_Pro_SLP_Carbon_Fiber_Air_Tank_68_4500_p/ninjatankpro-68slpdurablackout.htm). Accessed 19 December 2021
96. DeWALT: "D55146 - 1.6 HP Continuous. 225 PSI, 4.5 Gallon Compressor," [Online]. Available: <https://www.dewalt.com/products/storage-and-gear/air-compressors/16-hp-continuous-225-psi-45-gallon-compressor/d55146>. Accessed 19 December 2021
97. MAUER: "EMGR 90 L4," [Online]. Available: <https://www.motor-mauer.de/elektromotor-wechselstrom-lichtstrommotor-emgr-eas90l4-wechselstrommotor-einphasen-230-v-motor-shop-kaufen-1-1-kw-1500-min-1>. Accessed 19 December 2021
98. California Air Tools: "California Air Tools 8010A," [Online]. Available: <https://www.californiaairtools.com/ultra-quiet-series-of-air-compressor-contractor-grade/1-0-hp-air-compressors/cat-8010a/>. Accessed 19 December 2021
99. Kohki, Nitto: "DAH 110," [Online]. Available: <http://www.nitto-kohki.eu/en/products-en/pumps-a-compressors/dc-pumps/item/dah-110.html>. [Accessed 19 December 2021]
100. TOPSFLO: "TMD41A-A," [Online]. Available: <http://www.topsflo.com/mini-diaphragm-pump/tmd45-diaphragm-pump.html#Specifications>. Accessed 19 December 2021
101. Dandy, T.: Interviewee, *Topsflo Diaphragm Pump*. [Interview]. (2021)
102. Kohki, L. L. -. N: Interviewee, DAH 110 Information. [Interview]. (2021)
103. Mooney, L. M., Rouse, E. J., Herr, H. M.: "Autonomous Exoskeleton Reduces Metabolic Cost of Walking," in 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, pp. 1–11 (2014)
104. Bryan, G.M., Franks, P.W., Klein, S.C., Peuchen, R.J., Collins, S.H.: A Hip-knee-ankle exoskeleton emulator for studying gait assistance. *Int. J. Robot. Res.* **40**(4–5), 722–746 (2021)
105. Jin, X., Cui, X., Agrawal, S. K.: "Design of a Cable-driven Active Leg Exoskeleton (C-ALEX) and Gait Training Experiments with Human Subjects," in IEEE International Conference on Robotics and Automation, pp. 5578–5583, 2015.
106. Lee, Y., Lee, J., Choi, B., Lee, M., Roh, S.-G., Kim, K., Seo, K., Kim, Y.-J., Shim, Y.: Flexible Gait Enhancing Mechatronics System for Lower Limb Assistance (GEMS L-Type). *IEEE/ASME Trans. Mechatron.* **24**(4), 1520–1531 (2019)
107. Asbeck, A. T., Dyer, R. J., Larusson, A. F., Walsh, C. J.: "Biologically-inspired Soft Exosuit," in IEEE International Conference on Rehabilitation Robotics, pp. 1–8. (2013)
108. Mioskowska, M., Stevenson, D., Onu, M., Trkov, M.: "Compressed Gas Actuated Knee Assistive Exoskeleton for Slip-Induced Fall Prevention During Human Walking," in IEEE/ASME International Conference on Advanced Intelligent Mechatronics, pp. 735–740. (2020)
109. Kong, K., Jeon, D.: Design and Control of an Exoskeleton for the Elderly and Patients. *IEEE/ASME Int. Trans. Mechatronics* **11**(4), 428–432 (2006)
110. Schmidt, K., Duarte, J.E., Grimmer, M., Alejandro, S.-P.: The Myosuit: Bi-Articular Anti-gravity Exosuit That Reduces Hip Extensor Activity in Sitting Transfers. *Front. Neurobot.* **11**(57), 1–16 (2017)
111. M. Gloger, G. Obinata, E. Genda, J. Babjak and Y. Pei, "Active Lower Limb Orthosis with One Degree of Freedom for People with Paraplegia," in *International Conference on Rehabilitation Robotics*, pp. 258–263, 2017.
112. Van den Bogert, A.J.: Exotendons for Assistance of Human Locomotion. *Biomed. Eng. Online* **2**(17), 1–8 (2003)
113. Symons, C.: Interviewee, Carl Stahl Sava Industries steel cable 2081 Price. [Interview]. (2021)
114. Garcia, P.: Interviewee, Lexco 415310-00 outer cable Price. [Interview]. (2021)
115. Veneman, J.F., van der Helm, F.C., van der Kooij, H.: A Series Elastic- and Bowden-Cable-Based Actuation System for Use as Torque Actuator in Exoskeleton-Type Robots. *Int. J. Robot. Res.* **25**(3), 261–281 (2006)
116. Veneman, J.F., Kruidhof, R., Hekman, E.E.G., Ekkelenkamp, R., Van Asseldonk, E.H.F., van der Kooij, H.: Design and Evaluation of the LOPES Exoskeleton Robot for Interactive Gait Rehabilitation. *IEEE Trans. Neural Syst. Rehabil. Eng.* **15**(3), 379–386 (2007)
117. Maxon: "EC-4pole 30 Ø30 mm, brushless, 200 Watt," [Online]. Available: <https://www.maxongroup.com/maxon/view/product/motor/ecmotor/ec4pole/305013>. Accessed 21 November 2021

118. Nokon: "Products - Gear Systems," [Online]. Available: [http://www.nokon.com/NokonUSA\\_Products%20\(black\).htm](http://www.nokon.com/NokonUSA_Products%20(black).htm). Accessed 21 November 2021
119. Maxon: "EC-4pole 30 Ø30 mm, brushless, 200 Watt | High Power," [Online]. Available: <https://www.maxongroup.com/maxon/view/product/305015>. Accessed 21 November 2021
120. EC-i 40 Ø40 mm, brushless, 70 Watt, with Hall sensors, [Online]. Available: <https://www.maxongroup.com/maxon/view/product/449470>. Accessed 21 November 2021
121. Maxon: "EC-i 30 Ø30 mm, brushless, 75 W, with Hall sensors | High Torque," [Online]. Available: <https://www.maxongroup.com/maxon/view/product/539485>. Accessed 21 November 2021
122. Banala, S.K., Agrawal, S.K., Fattah, A., Krishnamoorthy, V., Hsu, W.-L., Scholz, J., Rudolph, K.: Gravity-Balancing Leg Orthosis and Its Performance Evaluation. *IEEE Trans. Rob.* **22**(6), 1228–1239 (2006)
123. Wiggin, B., Sawicki, G. S., Collins, S. H.: "An Exoskeleton Using Controlled Energy Storage and Release to Aid Ankle Propulsion," in International Conference on Rehabilitation Robotics, pp. 1–5 (2011)
124. Ranaweera, R., Mann, G., Gopura, R.C.: Development of a Passively Powered Knee Exoskeleton for Squat Lifting. *J. Robot. Netw. Artif. Life* **5**(1), 45–51 (2018)
125. Zhou, T., Xiong, C., Zhang, J., Chen, W., Huang, X.: Regulating Metabolic Energy Among Joints During Human Walking Using a Multiarticular Unpowered Exoskeleton. *IEEE Trans. Neural Syst. Rehabil. Eng.* **29**, 662–672 (2021)
126. Wu, P., Chen, X., He, Y., Liu, Z.: "Unpowered Knee Exoskeleton during Stair Descent," in The 7th International Conference on Mechatronics and Robotics Engineering, pp. 106–110. (2021)
127. Giovacchini, F., Vannetti, F., Fantozzi, M., Cempini, M., Cortese, M., Parri, A., Tingfang, Y., Lefeber, D., Vitiello, N.: A Light-Weight Active Orthosis for Hip movement assistance. *Robot. Auton. Syst.* **73**, 123–134 (2015)
128. Maxon: "EC 60 flat Ø60 mm, brushless, 100 Watt, with cover," [Online]. Available: <https://www.maxongroup.com/maxon/view/product/motor/ecmotor/ecflat/ecflat60/408057>. Accessed 18 December 2021
129. Kai, Y., Kitaguchi, S., Shotaro, K., Zhang, W., Tomizuka, M.: "Development of a Rehabilitation Robot Suit with Velocity and Torque-based Mechanical Safety Devices," in IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1380–1385. (2014)
130. Maxon: "RE 40 Ø40 mm, Graphite Brushes, 150 Watt," [Online]. Available: <https://www.maxongroup.com/maxon/view/product/148867>. Accessed 18 December 18
131. MiSUMi: "Round Wire Coil Springs/Deflection 45%/I.D. Referenced (VUR8–20)," [Online]. Available: <https://uk.misumi-ec.com/vona2/detail/110302604640/?HissuCode=VUR8-20>. Accessed 8 December 2021
132. Alouane, M.A., Huo, W., Rifai, H., Amirat, Y., Mohammed, S.: Hybrid FES-Exoskeleton Controller to Assist Sit-To-Stand Movement. *IFAC-PapersOnLine* **51**(34), 296–301 (2019)
133. Nikitczuk, J., Weinburg, B., Mavroidis, C.: "Rehabilitative Knee Orthosis Driven by Electro-Rheological Fluid Based Actuators," in IEEE International Conference on Robotics and Automation, pp. 2283–2289. (2005)
134. Zite, J. L., Ahmadkhanlou, F., Neelakantan, V. A., Washington, G. N.: "A Magnetorheological fluid based orthopedic active knee brace," in Smart Structures and Materials 2006: Industrial and Commercial Applications of Smart Structures Technologies, pp. 1–10. (2006)
135. Li, Y., Hashimoto, M.: Design and prototyping of a novel light-weight walking assist wear using PVC gel soft actuators. *Sens. Actuators* **239**, 26–44 (2016)
136. Cheng, C.-Y., Okamoto, S., Li, P., Akiyama, Y., Qiu, C., Yamada, Y.: "Encouragement of Squat-Lifting: Feasibility Study of a Highly Usable Passive Knee Assistive Device," in International Symposium on System Integration, pp. 504–508. (2020)
137. Yoshimi: "Shape memory alloy / taper wire φ1.5–0.7 × 300mm," [Online]. Available: <https://www.yoshimi-inc.com/shopbrand/ct32/>. Accessed 21 November 2021
138. Mueller Sports Medicine: "Self-Adjusting™ Hinged Knee Brace," [Online]. Available: <https://www.muellersportsmed.com/b2c-us/en/Open-Catalog/By-Sport/Gymnastics/SELF-ADJUSTING-HINGED-KNEE-BRACE-OSFM/p/6455>. Accessed 21 November 2021
139. Yoshizawa, N.: "Powered AFO for Achilles Tendon Rupture," in 30th Annual International IEEE EMBS Conference, pp. 4250–4253. (2008)
140. Washabaugh, E.P., Krishnan, C.: A Wearable Resistive Robot Facilitates Locomotor Adaptions during Gait. *Resorative Neurol. Neurosci.* **36**(2), 215–223 (2018)
141. K&J Magnetics, Inc.: "DX04B-N52," [Online]. Available: <https://www.kjmagnetics.com/proddetail.asp?prod=DX04B-N52>. Accessed 21 November 2021
142. Chaichaowarat, R., Macha, V., Wannasuphprasit, W.: "Passive Knee Exoskeleton Using Brake Torque to Assist Stair Ascent," in IEEE Region 10 Conference, pp. 1165–1170 (2020)
143. Misumi, "Warner series brake (Sinfonia Technology) (PB-260/FMS-AG)," [Online]. Available: <https://us.misumi-ec.com/vona2/detail/221004995844/?HissuCode=PB-260%2fFMS-AG>. Accessed 21 November 2021
144. Mankala, K. K., Banala, S. K., Agrawal, S. K.: "Passive Swing Assistive Exoskeletons for Motor-Incomplete Spinal Cord Injury Patients," in IEEE International Conference on Robotics and Automation, pp. 3761–3766. (2007)
145. Jin, S., Guo, S., Hashimoto, K., Xiong, X., Yamamoto, M.: "A Soft Wearable Robotic Suit for Ankle and Hip Assistance a Preliminary Study," in 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, pp. 1867–1870. (2018)
146. Pratt, G. A., Williamson, M. M.: "Series Elastic Actuators," in IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots, pp. 399–406. (1995)
147. Madden, J.D.W., Vandesteeg, N.A., Anquetil, P.A., Madden, P.G.A., Takshi, A., Pytel, R.Z., Lafontaine, S.R., Wieringa, P.A., Hunter, I.W.: Artificial Muscle Technology: Physical Principles and Naval Prospects. *IEEE J. Oceanic Eng.* **29**(3), 706–728 (2004)
148. Allen, D.P., Little, R., Laube, J., Warren, J., Voit, W., Gregg, R.D.: Towards an ankle-foot orthosis powered by a dielectric elastomer actuator. *Mechatronics* **76**(102551), 1–13 (2021)
149. Moltedo, M., Bacek, T., Junius, K., Vanderborcht, B., Lefeber, D.: "Mechanical Design of a Lightweight Compliant and Adaptable Active Ankle Foot Orthosis," in IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechanics, pp. 1224–1229 (2016)
150. SODEMANN Industrial Springs: "Compression Springs | Produced in Stainless Steel," SODEMANN, [Online]. Available: [https://www.industrial-springs.com/products/compression-springs/range-a-b-stainless-steel?a\\_004=29315\\_29315&a\\_006=33271\\_33284](https://www.industrial-springs.com/products/compression-springs/range-a-b-stainless-steel?a_004=29315_29315&a_006=33271_33284). Accessed 06 September 2021
151. Malkawi, S., Al-Nimr, M., Azizi, D.: A multi-criteria optimization analysis for Jordan's energy mix. *Energy* **127**, 680–696 (2017)
152. Pinto, D., Garnier, M., Baras, J., Chang, S.-H., Charlifue, S., Field-Fote, E., Furbish, C., Tefertiller, C., Mummidisetty, C.K., Taylor, H., Jayaraman, A., Heinemann, A.W.: Budget impact analysis of robotic exoskeleton use for locomotor training

- following spinal cord injury in four SCI Model Systems. *J. Neuroeng. Rehabil.* **17**(4), 1–13 (2020)
153. Brancato, E.L.: Estimation of Lifetime Expectancies of Motors. *IEEE Electr. Insul. Mag.* **8**(3), 5–13 (1992)
  154. Maxon: "Technology - short and to the point," November 2014. [Online]. Available: [https://www.maxongroup.com/medias/sys\\_master/root/8815461597214/DC-Technology-short-and-to-the-point-14-EN-30-31.pdf?attachment=true](https://www.maxongroup.com/medias/sys_master/root/8815461597214/DC-Technology-short-and-to-the-point-14-EN-30-31.pdf?attachment=true). Accessed 15 April 2022
  155. Woo, S.-W.: Estimating the Lifetime of the Pneumatic Cylinder in Machine Tool Subjected to Repetitive Pressure Loading. *J. US-China Public Adm.* **15**(5), 221–238 (2018)
  156. Bimba: "Cylinder Life Expectancy," May 2012. [Online]. Available: [https://airinc.net/wp-content/uploads/2014/08/Original-Line-Cylinder-Life\\_Expectancy-1.pdf](https://airinc.net/wp-content/uploads/2014/08/Original-Line-Cylinder-Life_Expectancy-1.pdf). Accessed 15 April 2022
  157. Baldor: "Cog-free Brushless Servo Motors," [Online]. Available: <https://literature.puertoricosupplier.com/024/MN23295.pdf>. Accessed 27 November 2021
  158. Baldor: "Servo, Linear & Motion Control," [Online]. Available: <http://www.rgspeed.com/assets/documents/feedback/baldor/servo-linear-and-motion-control.pdf>. Accessed 21 November 2021
  159. Copley Controls Corp.: "ServoTube Application Guide," [Online]. Available: <https://www.actronic-solutions.de/files/actronic/FTPROOT/Servotube-AppGuide.pdf>. Accessed 1 December 2021
  160. Kollmorgen: [Online]. Available: [https://www.kollmorgen.com/sites/default/files/public\\_downloads/s200\\_vts\\_e.pdf](https://www.kollmorgen.com/sites/default/files/public_downloads/s200_vts_e.pdf). Accessed 8 December 2020
  161. Elektromotoren: "Electric Motors," [Online]. Available: <https://www.motor-mauer.de/mediafiles/datasheets/EMGR/EMGR-Hauptkatalog.pdf>. Accessed 14 December 2021
  162. FESTO: "Valve series VOVG," [Online]. Available: [https://www.festo.com/cat/en-gb\\_gb/data/doc\\_ENUS/PDF/US/VOVG\\_ENUS.PDF](https://www.festo.com/cat/en-gb_gb/data/doc_ENUS/PDF/US/VOVG_ENUS.PDF). Accessed 19 December 2021
  163. Parker, C., Borisoff, J.F., Mortenson, W.B., Mattie, J.: A Survey of stakeholder perspectives on exoskeleton technology. *J. Neuroeng. Rehabil.* **11**(169), 1–10 (2014)
  164. Wang, S., Wang, L., Meijneke, C., Asseldonk, E. V., Hoewllinger, T., Cheron, G., Ivanenko, Y., Scaleia, V. L., Sylos-Labini, F., Molinari, M., Tamburella, F., Pisotta, I., Thorsteinsson, F., Ilzkovitz, M., Gancet, J., Nevatia, Y., Hauffe, R., Zanow F., Van der Kooij, H.: Design and Control of the MINDWALKER Exoskeleton. *IEEE Trans. Neural Syst. Rehabil. Eng.* **23**(2), 277–286 (2015)
  165. Bartenbach, V., Gort, M., Riener, R.: "Concept and Design of a Modular Lower Limb Exoskeleton," in International Conference on Biomedical Robotics and Biomechanics, pp. 649–654 (2016)
  166. Morichika, T., Kikkawa, F., Oyama, O., Yoshimitsu, T.: "Development of Walking Assist Equipment with Pneumatic Cylinder," in SICE Annual Conference, pp. 1058–1063. (2007)
  167. TSI Solutions: "173.5-DPY Bimba 1–1/2" x 3.5" Original Line Cyl," TSI Solutions, [Online]. Available: <https://www.tsisolutions.us/itemdetail/?itemCode=173.5-DPY>. Accessed 6 September 2021
  168. Dan: "Single-Acting Cylinders," Hydraulic Schematic Troubleshooting, 01 June 2018. [Online]. Available: [http://www.hydraulicstatic.com/20180601\\_single-acting-cylinders.html](http://www.hydraulicstatic.com/20180601_single-acting-cylinders.html). Accessed 04 Sep 2021
  169. Dan: "Double-Acting Cylinder with a Piston Rod on One Side," Hydraulic Schematic Troubleshooting, 09 May 2019. [Online]. Available: [http://www.hydraulicstatic.com/20190509\\_double-acting-cylinder-with-a-piston-rod-on-one-side.html](http://www.hydraulicstatic.com/20190509_double-acting-cylinder-with-a-piston-rod-on-one-side.html). Accessed 04 September 2021
  170. RS: "Bosch Rexroth Fixed Hydraulic Cylinder 100mm Stroke, 2952993400," [Online]. Available: <https://uk.rs-online.com/web/p/fixe-hydraulic-cylinders/2638556/>. Accessed 08 December 2021
  171. HosesDirect: "BLACK COMPRESSED AIR HOSE WITH YELLOW STRIPE 20 BAR AIR HOSE. 15/30/100M COILS," [Online]. Available: <https://www.hoses.co.uk/images/datasheets/BYA-6.pdf>. Accessed 10 December 2021

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Tom Slucock** received the B.Eng and M.Eng degrees in Electronic and Communications Engineering from the University of Kent, Canterbury, England in 2020. He is now working with the University of Kent on a PhD to develop a low-cost assistive lower-limb exoskeleton for users with pathologic gait disorders. His Research Interests include Robotics, Microcontrollers, and Exoskeletons.