Human Factors and Systems Interaction, Vol. 52, 2022, 57–65
https://doi.org/10.54941/ahfe1002139

Lower Limb Exoskeletons Some Examples of Application

Catarina Santos[1], Ana Teresa Gabriel[1,2], Cláudia Quaresma[2,3], and Isabel L. Nunes[1,2]

[1]UNIDEMI (FCT/UNL) - Research and Development Unit for Mechanical and Industrial Engineering, Portugal
[2]NOVA School of Sciences and Technology, NOVA University Lisbon, Portugal
[3]LIBPhys - UNL, Laboratory for Instrumentation, Biomedical Engineering and Radiation Physics, Portugal

ABSTRACT

Lower limb exoskeletons are wearable mechanical or mechatronic equipment developed as augmentative devices that work in concert with the user's movements to provide physical assistance through torques or structural support. The exoskeleton moves with the user and can act actively or passively, adding strength to the wearer. In addition, they allow maintaining human dexterity, agility, and adaptability (Bär et al., 2021). Depending on the field of application, these devices can be separated into two main categories: assistive and augmentation exoskeletons. Thus, assistive exoskeletons are designed to assist/replace the impaired parts of the users, restore physical movements, increase independence, and improve patients quality of life. Alternatively, augmentation exoskeletons can be found in industries to improve ergonomics, reduce the risk of exposure to demanding working conditions, prevent work accidents, reduce users' acute physical stress and strain and increase the operator's efficiency. As well as in military tasks to allow soldiers to carry heavy equipment while walking. Due to its wide use in various applications and the exponentially growing number of research studies in this area, the primary purpose of this article is to provide state of the art regarding lower limb exoskeletons, giving some examples of their general present-day use.

Keywords: Lower limb exoskeletons, Assistive exoskeletons, Augmentation exoskeletons

INTRODUCTION

Lower limb exoskeletons are wearable devices that focus on the wearer's mobility, helping users perform a wide range of tasks. This brief review divided lower limb exoskeletons into two types: augmentation and assistive exoskeletons, each used in a different field of application.

Augmentation exoskeletons can assist in daily living or working tasks, such as carrying or lifting heavy loads, reducing the burden in physically demanding tasks, walking, ascending/descending stairs, as well as in military tasks to allow soldiers to carry heavy equipment while walking (Bär et al., 2021; Ferreira et al., 2020; Flor et al., 2021; Mooney et al., 2014). Alternatively, lower limb assistive exoskeletons are used in the rehabilitation field to provide power assistance to help regain mobility and strength in a user's joint/limb motion where functionality is limited or lost. Moreover, these exoskeletons can also help elderly people perform activities of daily living. As people get older, they may lose their physical and cognitive faculties, compromising their ability to carry out basic life activities. Physical assistive exoskeletons can help in such situations to support elderly people remain independent and, in addition, reduce the burden on healthcare resources.

The research in lower limb exokeletons has been exponentially growing to achieve a model that can reproduce the required flexibility, optimize human well-being, the uniqueness of human motions, and the general system performance without causing discomfort and/or injuries. Therefore, the primary purpose of this article is to provide a state of the art of lower limb exoskeletons, giving some examples of assistive and augmentation exoskeletons.

LOWER LIMB ASSISTIVE EXOSKELETONS

The World Health Organization (WHO) has defined rehabilitation as "a set of interventions designed to optimize functioning and reduce disability in individuals with health conditions, in interaction with their environment". Assistive exoskeletons provide power assistance or restore motion in physically disabled, injured, or weak people who cannot walk due to various medical reasons, such as neurological disorders, stroke, and cerebral palsy. They can deliver highly controlled repetitive and intensive training, reduce the therapist intervention, and provide a quantitative assessment of motion and forces. Additionally, these exoskeletons can help or replace the impaired parts of the users, increase independence, improve elderly care, and improve the user's life quality (Gorgey et al., 2019; Vaughan-Graham et al., 2020; Bai et al., 2019).

This brief review identified 35 lower limb assistive exoskeletons (Bai et al., 2019; Bortole et al., 2015; Rodríguez-Fernández et al., 2021; Scilingo et al., 2022; Ishmael et al., 2019; Bock, 2008). This section describes some of these devices, which Table 1 also sums up by giving details related to their purpose, user requisites, and exoskeleton weight. As Table 1 shows, the available devices can assist in gait rehabilitation, in walking recovery for patients with neuromuscular impairments and paraplegia, be used by amputees, and improve the quality of life of healthy elderly. In general, the structure of the exoskeletons can adapt to the anthropometry of most of the population. However, the maximum allowed weight can be a limiting factor for the obese population. Concerning the device weight, the exoskeletons are still heavy and bulky devices due to their rigid structures, actuators, and batteries.

Lower limb assistive exoskeletons assists the user by controlling the joint's movement during the training sessions. Some examples are H2 Exoskeleton and LOPES, used in gait rehabilitation, and ReWalk and EksoNR, which assist people with paraplegia in performing movements such as standing and walking.

H2 Exoskeleton is a lower limb exoskeleton designed for the recovery of stroke patients. It is lightweight and battery-powered and has six electric

Table 1. Overview of currently available lower extremity assistive exoskeletons.

Name	Application	User height	Max. user weight	Weight
H2 Exoskeleton	Rehabilitation	150–195 cm	100 kg	12 kg
LOPES	Rehabilitation	<185 cm	90 kg	-
ReWalk	Locomotion	160–190 cm	100 kg	23.3 kg
EksoNR	Locomotion	150–188 cm	100 kg	23 kg
Utah Lightweight Hip	Amputees	-	-	2.45 kg
C-Leg	Amputees	-	136 kg	1.2 kg
AXO-SUIT	Elderly care	-	-	25 kg

actuated joints (including hip, knee, and ankle). The device has an assistive gait control algorithm to create a force field along a desired trajectory, which only applies torque when patients deviate from the prescribed movement pattern. The impedance controller uses the concept of assistance as needed; it only assists the patient when they cannot complete the gait movements (Bortole et al., 2015). LOPES is designed for use in training on a treadmill and aims to make the rehabilitation process more effective for patients and less demanding for therapists. The device combines a freely translatable and 2D-actuated pelvis segment, containing two DOF for the horizontal pelvis translation, with a leg exoskeleton containing three actuated rotational joints, two at the hip and one at the knee. The joints are impedance controlled to allow bidirectional mechanical interaction between the device and the user (Veneman et al., 2007). These two devices differ as the H2 Exoskeleton is an overground exoskeleton that helps the patients regain overground gait, and LOPES is a treadmill-based exoskeleton, which promotes gait training sessions on a treadmill. Treadmill-based exoskeleton sometimes requires manual assistance by therapists, which can lead to poor coordination and synchronization of movements in both legs, and fatigue of the therapist can limit the efficacy of the therapy (Bortole et al., 2015).

Concerning the exoskeletons to assist patients who have an impairment of motor or sensory function of the lower limbs, ReWalk is an excellent example for upright walking. ReWalk was developed in 2006 by Argo Medical Technologies Ltd and received FDA approval in 2014 for use both in a clinical setting and in the home or community environment. It was the first exoskeleton to receive FDA approval for individuals with spinal cord injuries (SCI) of T4 to L5. The device enables individuals with SCI to stand upright, walk, turn, climb, and descend stairs by using rechargeable batteries to drive the hip and knee joint motors. It uses a tilt sensor to compute the trunk angle and a wristwatch-style controller to activate different motion modes (ReWalk Robotics, n.d.). Another example is EksoNR received FDA approval in 2020, becoming the first to have FDA clearance for rehabilitation use for acquired brain injury patients. EksoNR is a powered hip-knee medical rehabilitation exoskeleton that gives trajectory assistance and the necessary support to the spine, trunk, and legs (including hip, knee, and ankle joints), allowing users to regain their full functional mobility. This exoskeleton has six DOF in total (i.e., tree DOF per leg). The hip and knee joints are active and can assist in the sagittal plane, and ankle joints are passive. The clinician can vary the power provided to each leg, depending on the walking ability of the user, and control when the Ekso stands, sits, and takes a step via a control pad (Ekso Bionics, 2021).

It is also crucial to highlight the use of lower limb exoskeletons for amputees in the rehabilitation field. In this case, the exoskeletons aim to support the person by providing the missing limb, and they should have an active actuation method and a control system to assist the movements. Therefore, these powered devices overcame a limitation of conventional lower-limb prostheses, which cannot imitate leg movements to actively propel ambulation, so it is common for amputees to resort to compensation strategies, which can lead to unnatural gait patterns that overload the residual limb articulations (Nolan & Lees, 2000). One example of exoskeletons used for amputees is Utah Lightweight Hip Exoskeleton, which is a device used in above-knee amputees and has the advantage to be lighter than the other available powered devices without reducing the performance (Ishmael et al., 2019; Baimyshev et al., 2018; Lenzi et al., 2018). Another example is C-Leg, which is used chiefly with trans-femoral amputees. Ottobock is the developer of C-Leg, which is a world leader in amputee's robotic prostheses and orthoses (Bock, 2008; Segal et al., 2006).

Utah Lightweight Hip Exoskeleton is a lightweight powered unilateral hip exoskeleton that can easily interface with the user's residual limb at the socket level using a flexible, 3D printed interface. This device provides assistive torque to the user's residual limb in flexion and extension direction while allowing for passive abduction and adduction. By assisting the movements of the residual joints, its mass has a lower negative impact on the metabolic expenditure than a powered prosthesis. The exoskeleton can synchronize with the user's gait by combining information on the hip position and leg acceleration from the onboard sensors, providing the desired assistance profile in the phase with walking. The experimental results suggest that the device can decrease walking effort compared to walking without the exoskeleton (Ishmael et al., 2019).

Ottobock designed the C-Leg. The presentation of the next generation of the C-Leg was in 2011, but this device has existed since 1997, being the first prosthesis system to control and adapt to an individual's gait intelligently. It is a microprocessor-controlled hydraulic prosthetic knee based on strain gauges in the tube adapter and knee angle sensor, which dynamically adapts to all walking speeds in real-time. The leg prosthesis system has the following advantages: permanent stance phase control, the ability to weight the prosthesis during flexion, dynamic alignment, lower energy expenditure while walking, and the fact that it allows for natural physiological movements that help protect the rest of the user's body (Bock, 2008; Segal et al., 2006).

Additionally, in promoting the quality of life of healthy elderly, the AXO-SUIT exoskeleton can be beneficial, as it provides flexible physical assistance as needed. The system consists of lower-body and upper-body modules, and their combination as full body. The full-body exoskeleton comprises twenty-seven DOF, of which seventeen are passive and ten active. The device can

Table 2. Overview of currently available lower extremity exoskeletons for human strength augmentation.

Category	Name	Application	Load conditions	Weight
Military	FORTIS K-SRD	Strength assistance	18.14 kg	12.24 kg
	Dephy ExoBoot	Strength assistance	-	2.12 kg
Workers	Hercule V3	Strength and squatting	100 kg	30 kg
	LegX	Squatting	-	6.2 kg

assist people in walking, standing, carrying, and handling tasks (Bai et al., 2019).

LOWER LIMB AUGMENTATION EXOSKELETONS

Lower extremity exoskeletons developed for human strength augmentation can enhance human strength and endurance during locomotion. This section includes two subtopics: soldiers and industrial workers, each for different purposes. Lower limb exoskeletons are helpful for military purposes, such as carrying heavy equipment and walking fast over rough terrain. Additionally, exoskeletons are helpful for industrial workers to perform physically demanding tasks, seeking the avoidance of long-term physical damages, due to tasks such as prolonged standing or squatting, and improving work efficiency.

This brief review identified 21 lower limb augmentation exoskeletons (Bär et al., 2021; Hamza et al., 2020). The subsections below give examples of lower limb exoskeletons, which Table 2 also sums up by giving details related to their purpose, load condition, and exoskeleton weight. As Table 2 shows, the exoskeletons can increase human power due to the support of the addressed musculoskeletal structures and support users during repeated or prolonged squatting activities.

For Soldiers

These exoskeletons aim to amplify soldiers' capabilities to perceive less of the actual load carried, allowing them to travel long distances with reduced metabolic costs (Dollar & Herr, 2008). One example in this field is FORTIS K-SRD, tested in an independent study performed by the University of Michigan Human Neuromechanics Laboratory, suggesting that the knee exoskeleton can reduce the metabolic cost of walking uphill conditions. Another example is Dephy ExoBoot, the first autonomous robotic ankle exoskeleton to reduce the energy cost of walking without the exoskeleton.

FORTIS K-SRD is a computer-controlled exoskeleton that counteracts overstress on the lower back and legs, increasing mobility and load-carrying capability. It boosts leg capacity for physically demanding tasks that require repetitive or continuous kneeling/squatting, lifting, dragging, carrying, or climbing with heavy loads (Lockheed Martin, 2017). Dephy ExoBoot gives the user assistance at the ankle joint while performing challenging physical tasks, such as walking while carrying a heavy load. The device has a brushless DC motor mounted on a rigid shank that assists the user by generating torque through a belt-drive transmission, which applies force on a boot-mounted structure. The exoskeleton uses a combination of mechanical sensors, models of human behavior, and machine learning to determine how and when to assist the user (Mooney et al., 2014).

For Industrial Workers

Workers in industrial environments often perform physically demanding tasks, leading to stress and adverse effects on their health. The tasks can include lifting heavy parts for fitting on an assembly line or handling heavy equipment in pick and place operations. The use of exoskeleton in industrial environments can improve workplace ergonomics, reduce the risks of work accidents, reduce users' acute physical stress and strain and increase the operator's efficiency (Bär et al., 2021).

One example of industrial exoskeletons is the Hercule V3, an active support exoskeleton that can help users during walking, squatting, and lifting heavy objects. The device has two sets of electricity-powered servo actuators placed on the knee and hip joints, which help reduce the waist's burden when the upper limbs lift heavy objects. The exoskeleton has two mechanical legs and can support loads up to 40 kg (Yan et al., 2021). Another example is legX, developed by SuitX, to support the user's knees during repeatedly or prolonged squatting activities. The legX provides two modes: a (dynamic) spring assistance mode and a locked mode. In the spring assist mode, the exoskeleton stores energy during knee flexion to cradle the person while lowering to a squatted position and releases that energy during knee extension to augment the muscles while rising to a standing position. The legX exoskeleton also has two different levels of support in the spring assist mode, which provide different amounts of supporting force to the user. The level of spring assistance can be adjusted to accommodate preference or the worker's weight. During the locked mode, the user is seated at a predetermined angle, and the exoskeleton supports the upper body weight. In spring assist and locking modes, the supportive force is applied along the buttocks and shins of the users and transferred to the ground. The locking mode is beneficial for static tasks, while the spring assistance mode is beneficial for dynamic tasks where the working height varies. This device significantly reduces rectus femoris activity during squatted static (floor) and dynamic (panel) work and may reduce pain and discomfort associated with squatting and potentially reduce the risk of developing knee disorders (*LegX | Suitx*, n.d.; Pillai et al., 2020).

CONCLUSION

This article has presented a brief review of lower-limb wearable exoskeletons by giving some application examples.

Lower limb exoskeletons have a positive effect in a wide field of application, from assistive devices in the rehabilitation field to power augmentation for industrial and military work. For instance, using these devices can have an essential role in therapy assistance, gait rehabilitation (especially among SCI and stroke patients), and elderly care, for example, by releasing the burden of therapists, increasing independence, allowing the opportunity of independent home training, and providing effective and repetitive gait training by giving sensor-based motion feedback. Nevertheless, some of these devices are still heavy and bulky, requiring supervision (usually from clinical staff) and walking aids, which hinders mobility and independence. Additionally, joint misalignment is also an issue in current exoskeletons, which may increase metabolic cost and discomfort of the wearer, reduce the power-assisted effect, and it could lead to skin abrasions and increase risk of fracture (Ishmael et al., 2019; Rodríguez-Fernández et al., 2021; Scilingo et al., 2022). In addition, it is also promising in the industry or military work to amplify soldiers' capabilities to perceive less of the actual load carried and assist workers with heavy load tasks, or prolonged standing/squatting tasks, by reducing physical fatigue and muscle activity, and loading. However, lower limb exoskeletons can bring additional risks, such as load shifting and redistribution of a wearer's center of gravity (Luger et al., 2019; Wang et al., 2020; Zhu et al., 2018).

Therefore, even though the application of lower limb exoskeletons in these fields can bring many advantages, it is essential to highlight the critical importance of dynamic and static balance, prevention of falling, ensuring controller stability and smooth human-exoskeleton interaction in the development of these devices, in order to guarantee the safety of users.

In the future, the fact that the use of exoskeletons has already had a positive impact on different fields and the potential for the use of these devices is broadening can significantly increase exoskeletons research to develop lightweight and ease-to-use devices.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support of FCT.IP-UIDB/00667/2020.

REFERENCES

Bai, S., Christensen, S., Islam, M., Rafique, S., Masud, N., Mattsson, P.,O'Sullivan, L., & Power, V. (2019). Development and testing of full-body exoskeleton AXO-SUIT for physical assistance of the elderly. *Biosystems and Biorobotics*, *22*, 180–184. https://doi.org/10.1007/978-3-030-01887-0_35

Baimyshev, A., Lawson, B., & Goldfarb, M. (2018). Design and Preliminary Assessment of Lightweight Swing-Assist Knee Prosthesis. Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS, 3198–3201. https://doi.org/10.1109/EMBC.2018.8513087

Bär, M., Steinhilber, B., Rieger, M. A., & Luger, T. (2021). The influence of using exoskeletons during occupational tasks on acute physical stress and strain compared to no exoskeleton – A systematic review and meta-analysis. *Applied Ergonomics*, *94*. http://10.0.3.248/j.apergo.2021.103385

Bock, O. (2008). *C-Leg ® Product Line*. www.ottobock.com

Bortole, M., Venkatakrishnan, A., Zhu, F., Moreno, J. C., Francisco, G. E., Pons, J. L., & Contreras-Vidal, J. L. (2015). The H2 robotic exoskeleton for gait rehabilitation after stroke: Early findings from a clinical study Wearable robotics in clinical testing. *Journal of NeuroEngineering and Rehabilitation*, *12*(1). https://doi.org/10.1186/s12984-015-0048-y

Dollar, A. M., & Herr, H. (2008). Lower extremity exoskeletons and active orthoses: Challenges and state-of-the-art. *IEEE Transactions on Robotics*, *24*(1), 144–158. https://doi.org/10.1109/TRO.2008.915453

Ekso Bionics. (2021). *EksoNR - The Next Step in NeuroRehabilitation - Ekso Bionics*. Retrieved January 10, 2022, from https://eksobionics.com/eksonr/

Ferreira, G., Gaspar, J., Fujão, C., & Nunes, I. L. (2020). Piloting the Use of an Upper Limb Passive Exoskeleton in Automotive Industry: Assessing User Acceptance and Intention of Use. *Advances in Intelligent Systems and Computing*, *1207 AISC*, 342–349. https://doi.org/10.1007/978-3-030-51369-6_46

Flor, R., Gaspar, J., Fujão, C., & Nunes, I. L. (2021). How Workers Perceive LAEVO Exoskeleton Use in Non-cyclic Tasks. *Lecture Notes in Networks and Systems*, *265*, 147–154. https://doi.org/10.1007/978-3-030-79816-1_19

Gorgey, A. S., Sumrell, R., & Goetz, L. L. (2019). Exoskeletal Assisted Rehabilitation After Spinal Cord Injury. *Atlas of Orthoses and Assistive Devices*, 440–447.e2. https://doi.org/10.1016/B978-0-323-48323-0.~00044--5

Hamza, M. F., Ghazilla, R. A. R., Muhammad, B. B., & Yap, H. J. (2020). Balance and stability issues in lower extremity exoskeletons: A systematic review. Biocybernetics and Biomedical Engineering, 40(4), 1666–1679. http://10.0.3.248/j.bbe.2020.09.004

Indego. (n.d.). *Indego | Powering People Forward*. Retrieved January 21, 2022, from http://www.indego.com/indego/us/en/home

Ishmael, M. K., Tran, M., & Lenzi, T. (2019). ExoProsthetics: Assisting above-knee amputees with a lightweight powered hip exoskeleton. *IEEE International Conference on Rehabilitation Robotics*, *2019-June*, 925–930. https://doi.org/10.1109/ICORR.2019.8779412

legX | suitx. (n.d.). Retrieved January 11, 2022, from https://www.suitx.com/legx

Lenzi, T., Cempini, M., Hargrove, L., & Kuiken, T. (2018). Design, development, and testing of a lightweight hybrid robotic knee prosthesis. International Journal of Robotics Research, 37(8), 953–976. https://doi.org/10.1177/0278364918785993

Lockheed Martin (2017) New Lockheed Martin Exoskeleton Helps Soldiers Carry

Heavy Gear, Lockheedmartin.Com. Available at: https://news.lockheedmartin.com/2017-05-16-New-Lockheed-Martin-Exoskeleton-Helps-Soldiers-Carry-Heavy-Gear?_ga=2.257684616.2035891536.1564607389-431268198.1564607389.

Luger, T., Seibt, R., Cobb, T. J., Rieger, M. A., & Steinhilber, B. (2019). Influence of a passive lower-limb exoskeleton during simulated industrial work tasks on physical load, upper body posture, postural control and discomfort. *Applied Ergonomics*, *80*, 152–160. https://doi.org/10.1016/j.apergo.2019.05.018

Mooney, L. M., Rouse, E. J., & Herr, H. M. (2014). Autonomous exoskeleton reduces metabolic cost of human walking during load carriage. *Journal of NeuroEngineering and Rehabilitation*, *11*(1). https://doi.org/10.1186/1743-0003-11-80

Nolan, L., & Lees, A. (2000). The functional demands on the intact limb during walking for active trans-femoral and trans-tibial amputees. *Prosthetics and Orthotics International*, *24*(2), 117–125. https://doi.org/10.1080/03093640008726534

Pillai, M. V, Van Engelhoven, L., & Kazerooni, H. (2020). Evaluation of a Lower Leg Support Exoskeleton on Floor and Below Hip Height Panel Work. *Human Factors*, *62*(3), 489–500.

ReWalk Robotics. (n.d.). *ReWalk Robotics - More Than Walking*. USA. Retrieved January 7, 2022, from https://rewalk.com/

REX Bionics. (n.d.). *Clinical use - Rex Bionics*. Retrieved January 21, 2022, from https://www.rexbionics.com/rex-for-clinical-use/

Rodríguez-Fernández, A., Lobo-Prat, J., & Font-Llagunes, J. M. (2021). Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments. Journal of NeuroEngineering andRehabilitation 2021 18:1, 18(1), 1–21. https://doi.org/10.1186/S12984021-00815-5

Scilingo, P., Wang, T., Zhang, B., Liu, C., Liu, T., Han, Y., Wang, S., Ferreira, J. P., Dong, W., & Zhang, X. (2022). A Review on the Rehabilitation Exoskeletons for the Lower Limbs of the Elderly and the Disabled. Electronics 2022, Vol. 11, Page 388, 11(3), 388. https://doi.org/10.3390/ELECTRONICS11030388

Segal, A. D., Orendurff, M. S., Klute, G. K., McDowell, M. L., Pecoraro, J. A., Shofer, J., & Czerniecki, J. M. (2006). Kinematic and kinetic comparisons of transfemoral amputee gait using C-Leg® and Mauch SNS® prosthetic knees. *Journal of Rehabilitation Research and Development*, *43*(7), 857–870. https://doi.org/10.1682/JRRD.2005.09.0147

Vaughan-Graham, J., Brooks, D., Rose, L., Nejat, G., Pons, J., & Patterson, K. (2020). Exoskeleton use in post-stroke gait rehabilitation: a qualitative study of the perspectives of persons post-stroke and physiotherapists. *Journal of NeuroEngineering & Rehabilitation (JNER)*, *17*(1). http://10.0.4.162/s12984-020-00750-x

Veneman, J. F., Kruidhof, R., Hekman, E. E. G., Ekkelenkamp, R., Van Asseldonk, E. H. F., & Van Der Kooij, H. (2007). Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *15*(3), 379–386. https://doi.org/10.1109/TNSRE.2007.903919

Wang, T., Zhu, Y., Zheng, T., Sui, D., Zhao, S., & Zhao, J. (2020). PALExo: A Parallel Actuated Lower Limb Exoskeleton for High-Load Carrying. *IEEE Access, Access, IEEE*, *8*, 67250–67262. https://doi.org/10.1109/ACCESS.2020.2986357

Zhu, A., Shen, Z., Shen, H., Wu, H., & Zhang, X. (2018). Design of a Passive Weight-Support Exoskeleton of Human-Machine Multi-Link. *2018 15th International Conference on Ubiquitous Robots (UR)*, 296–301. https://doi.org/10.1109/URAI.2018.8441899