Exoskeletons: a review of recent progress

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Abstract

Purpose – This paper aims to provide an insight into recent developments in the robotic exoskeleton business by considering research, corporate activities, products and emerging applications.

Design/methodology/approach – Following a short introduction, this first provides examples of exoskeleton research involving artificial intelligence (AI). It then identifies recent market entrants and their products and discusses emerging industrial applications. Finally, conclusions are drawn.

Findings – The exoskeleton business is in a highly dynamic state. A research effort involving AI techniques seeks to impart exoskeletons with greatly enhanced capabilities, particularly in clinical applications. Many new companies have been established during the past decade, and several are exploiting academic research. The majority are targeting applications in the clinical market. The industrial sector is viewed as a key growth area, but applications remain limited, although some exist for robotic gloves, upper-body, waist and lower-body devices in the logistics, construction, automotive and other industries. Industrial applications for full-body exoskeleton are yet to progress beyond the trial stage.

Originality/value – This provides details of recent academic and corporate developments and emerging industrial applications in the robotic exoskeleton business.

Keywords Robot, Exoskeleton, Artificial intelligence, Applications

Paper type Technical paper

Introduction

Robotic exoskeletons are wearable, powered electromechanical devices that seek either to enhance an able-bodied user’s strength or endurance or to help restore motor functions in the disabled. Aimed at augmenting the wearer’s strength and lifting capacity, the first powered exoskeleton, the Hardiman, was developed in the mid-1960 in the US by General Electric. It used electro-hydraulic actuation but technological limitations of the day prevented its deployment. The first exoskeletons for gait assistance were developed in 1969 at the Mihajlo Pupin Institute in Serbia, which were pneumatically powered and allowed users to adopt a near-anthropomorphic gait.

In the following decades, exoskeletons attracted growing interest from the academic community and commercial enterprises, and the technology has progressed greatly from advances in actuators, sensors, materials, power sources, control techniques, software and, more recently, artificial intelligence (AI). Although most early developments were aimed at military and clinical applications, the technology is now starting to find industrial uses, potentially leading to significant market growth. According to Fortune Business Insights, the global wearable robotic exoskeleton market was valued at US$671.6m in 2021, US$952.5m in 2022 and is forecast to reach US$11,995.7m by 2029, rising at a CAGR of 43.6%. This article aims to provide details of recent exoskeleton research, product developments and applications.

The role of artificial intelligence

As with many other fields of robotics, exoskeleton design and performance are progressing from the application of AI techniques which will arguably confer greater benefits than any other field of prevailing research. Recent work at the Canadian University of Waterloo has combined computer vision and deep-learning AI to mimic a human-like gait (Laschowski et al., 2020). Using a lightweight wearable camera [Figure 1 (a)], over 5.6 million RGB images of indoor and outdoor walking environments were captured throughout the summer, autumn and winter months [Figure 1 (b)] to create the ExoNet database. Approximately 923,000 of the images were human-annotated using a novel, 12-class hierarchical labelling architecture [Figure 1 (c)]. The group then trained and tested the EfficientNetB0 convolutional neural network, which was optimised for efficiency using neural architecture search, a technique for automating the design of artificial neural networks, to predict the forward walking environments. The system achieved an image classification accuracy of approximately 73%, and in addition to robotic leg prostheses and exoskeletons, applications of ExoNet could include humanoids, autonomous legged robots, powered wheelchairs and other assistive mobility devices. The next phase of the ExoNet project will involve sending instructions to motors so that robotic exoskeletons can climb stairs, avoid obstacles or take other appropriate actions based on an analysis of the user’s current movement and the forthcoming terrain. Additionally, the group seeks to improve the energy efficiency of the exoskeleton’s motors by using human motion to charge the batteries. Preliminary results were recently reported (Laschowski et al., 2021) and showed that robotic exoskeletons and prostheses
could regenerate approximately 26 Joules of electrical energy while sitting down, compared to approximately 19 Joules per walking stride.

Recent research by workers from Riken and the universities of Kyushu and Kyoto involves a lower-body exoskeleton and electromyography (EMG) based movement classification method (Furukawa et al., 2022). The lightweight knee exoskeleton comprises a carbon fibre frame and a highly back-drivable joint driven by a pneumatic artificial muscle. The AI technique, namely, a positive-unlabelled (PU) classifier, was used to predict the user’s intended motions and exploited processed EMG signals for hip and knee angles and trunk velocity. The PU classification method allows the use of ambiguous data by combining positively labelled data, which the machine knows is correct, with other unlabelled data that might either be positive or negative, allowing the AI system to learn from data that is not all labelled. Experiments were conducted with five healthy subjects to assist sit-to-stand movements from four possible motions. The PU approach was compared with two classification methods that assume fully labelled data, and the results showed that all subjects’ movements were correctly assisted. Figure 2 shows details of the exoskeleton and the PU-based AI technique, and Figure 3 shows a test subject using the system to stand.

Figure 1 Development of the ExoNet database (a) photograph of the wearable camera system used for data collection; (b) examples of the high resolution RGB images of human walking environments and (c) schematic of the 12-class hierarchical labelling architecture (Credit: Laschowski et al., 2020, Frontiers in Robotics and AI. doi: 10.3389/frobt.2020.562061)

Figure 2 (a) The carbon fibre robotic exoskeleton. (b) The selective assist strategy. In this approach, the assistive policy is selected among candidate daily motions by using an EMG-based movement classification method constructed in a PU learning framework to assist the user’s motion (Credit: Furukawa et al., 2022, IEEE Robotics and Automation, doi: 10.1109/LRA.2022.3148799)
Research by workers from the University of Pittsburgh, NC State University and the University of Wisconsin-Milwaukee combines a powered exoskeleton with the functional electrical stimulation (FES) technique ([Molazadeh et al.], 2021). FES is often prescribed to reanimate standing and walking functions in people with spinal cord injury and other gait disorders but causes a rapid onset of muscle fatigue. However, supplementing FES-induced muscle contractions with robotic assistance, so-called hybrid exoskeleton systems, reduces the overall stimulation duty cycle, thereby delaying the onset of muscle fatigue during high torque physical exercises such as sit-to-stand tasks. In this work, a higher-level neural network-based iterative learning controller is used to generate the torques needed to drive the system. Then, a low-level model predictive control-based allocation strategy optimally distributes the torque contributions between FES and the exoskeleton’s knee motors based on the muscle fatigue and recovery characteristics of a participant’s quadriceps muscles. Trials with four able-bodied participants validated the effectiveness of the system, and the RMS error of the knee joint and the hip joint was reduced by 71.96% and 74.57%, respectively, in the fourth iteration compared to the error in the first sit-to-stand iteration. Importantly, unlike powered exoskeletons that passively move the limbs, FES-induced active muscle contractions contribute to neuroplasticity that may eventually lead to the recovery of the lost limb function. Figure 4 shows a schematic of the system.

Workers from the University of Texas at Austin have developed a lower-limb exoskeleton control technique for user-intent recognition, which combines surface EMG with sonomyography ([Rabe and Fey], 2022). Sonomyography is the real-time dynamic ultrasound imaging of skeletal muscle, but in contrast to EMG, its ability to predict multiple lower-limb joint kinematics during ambulation tasks and its potential as an input for multiple DOF assistive devices is unknown. This research aimed to evaluate surface EMG and sonomyography, as well as the fusion of features from both modalities, as inputs to Gaussian process regression (GPR) models for the continuous estimation of hip, knee and ankle angle and velocity during various walking and ascent/descent tasks. GPR is a Bayesian, probabilistic supervised machine learning framework that has been used widely for regression and classification tasks and can make predictions incorporating prior knowledge and provide uncertainty measures over predictions. Time-intensity features of sonomyography on both the anterior and posterior thigh along with time-domain features of surface EMG from eight muscles on the lower limb were used to train and test subject-dependent and task-invariant GPR models for the continuous estimation of hip, knee and ankle motion. It was found that anterior sonomyography sensor fusion with surface EMG significantly improved estimation of hip, knee and ankle motion for all ambulation tasks in comparison to surface EMG alone. Additionally, anterior sonomyography alone significantly improved errors at the hip and knee for most tasks compared with surface EMG. Figure 5 shows a schematic overview of the method.

Corporate activities and products and applications

In parallel with the academic effort, corporate activity is rapidly gaining pace. In addition to established manufacturers such as ReWalk, Ekso Bionics, Sarcos and others, many new companies have entered the market during the past decade. Based in Paris, Wandercraft was founded in 2012 and produced the Atalante X lower-body exoskeleton, which is
aimed at the rehabilitation of individuals suffering from complete or partial paraplegia. A key feature is the innovative self-balancing function which allows hands-free operation. Spanish Marsi Bionics was founded in 2013 and manufactures the Atlas, which is the only wearable gait exoskeleton for use by children with neuromuscular diseases, and the marsi active knee, a single-DOF device for use in gait rehabilitation in patients affected by hemiplegia or severe knee weakness. Also based in Spain, Gogoa Mobility Robots was founded in 2015. It produces Hank, a lower-body exoskeleton that features six driven joints on the hip, knee and ankle, which allow users to move in a less “robotic” and more human manner. Other products include Belk, and a knee exoskeleton aimed a rehabilitation and the Hand of Hope, an electromyographic hand exoskeleton that assists patients during recovery from a stroke. Gogoa was the first European company to obtain the CE mark for an exoskeleton aimed at lower-limb rehabilitation. A further Spanish start-up is Able Human Motion, established in 2018 as a spin-out from the Universitat Politàcnica de Catalunya. It produces a lower-body exoskeleton, which is broadly similar to other products which seek to assist individuals with spinal cord injuries. Wearable Robotics is a spin-off from the Scuola Superiore Sant’Anna of Pisa, Italy and was founded in 2014. It produces the ALEX, a six DOF exoskeleton, which is aimed at the neuromotor rehabilitation of upper limb function and the Track-Hold, a rehabilitation device for passive upper limb training. ExoAtlet is a Russian company with European headquarters in Luxembourg and was founded in 2013 following research at the Moscow State University Research Institute of Mechanics, where a team won a public tender for the creation of an exoskeleton for emergency rescue operations. It now produces a family of robotic and passive exoskeletons aimed at industrial applications. These include the MAPS-E, an upper-body exoskeleton with four DOF; the HEMS-L, a waist-mounted device that allows the user to carry up to 50 kg; and the HEMS-GS, a lower limb exoskeleton.

As illustrated above, the emphasis of research and most new product developments is the clinical market which is the best established, but industrial applications are starting to emerge. While passive exoskeletons are finding rapidly growing uses in a range of industries, principally to reduce repetitive strain injuries (RSI), robotic devices are only starting to be deployed and most applications remain at the trial stage. However, the potential benefits are significant: in addition to reducing the incidence of RSI and other injuries, robotic exoskeletons allow workers to handle greater loads and suffer reduced fatigue, and possibly also eliminate the need for specialised lifting equipment, thereby increasing productivity and reducing costs.

One device starting to find industrial uses is the Ironhand, produced by Bioservo Technologies, a Swedish company that was
founded in 2006 through a collaboration between researchers at the Royal Institute of Technology and a neurosurgeon at Karolinska University Hospital. The Ironhand 2.0 (Figure 7) is a powered robotic glove that in contrast to the OneGrip, is aimed at augmenting gripping force in able-bodied users. The present version is equipped with artificial tendons and pressure sensors located on the palm and in the fingers’ middle phalanges and tips which detect when the user grasps an object and triggers the servo motors in the power pack. A microcomputer then calculates the amount of power required and small motors activate the tendons. As a result, the finger joints flex, and gripping is performed with less force required by the operator. The harder the user grips, the more force is applied, to a maximum of 16 N per finger. By reducing the amount of force and strain on the user’s tendons, the Ironhand decreases the risk of injury. The system’s Smart Assist function uses machine learning and adapts the behaviour of the glove according to how the operator is using it. In 2020 Japanese construction machinery rental business Nishio and Bioservo signed an agreement to rent and sell Ironhand to the construction and maintenance industries in Japan, and in 2022 Nisho ordered 10 units. In the USA, Rhino Tool House, a provider of advanced industrial engineering solutions, has delivered systems to companies in the automotive, construction and consumer product manufacturing industries and in 2021, industrial equipment rental giant Loxam ordered units for use in the French construction and civil engineering industries. A video showing the system in use can be viewed at: https://youtu.be/mOu53LeD5ok.

The technology underpinning the Ironhand was originally developed as part of a General Motors initiative to use robotic hand technology for a NASA robot. The company has recently been conducting successful trials at several of its plants with the Ironhand and the passive SuitX MAX (Modular Agile exoskeleton) and maintains that the two products could be combined to yield a more complete strength-enhancing exoskeleton.

Full-body and lower-body exoskeletons that enhance the user’s strength have attracted much interest from various industrial sectors, but few are yet to find routine uses. In 2018 LG Electronics unveiled the CLOi SuitBot (Figure 8), a lower-body exoskeleton designed in collaboration with the start-up SG Robotics. It was aimed at increasing leg strength and endurance and could connect to other LG service robots to become part of a smart working network to deliver information and tools required in industries such as manufacturing, logistics and distribution. However, it has not yet entered production. Military contractor Lockheed Martin, best known for its military exoskeletons, now produces the ONYX, a lower-body exoskeleton. This arose from a collaboration that started in 2016 with B-Temia, a Canadian manufacturer of lower-body rehabilitation exoskeletons. Although ONYX has military applications and is not aimed at mainstream industrial uses, it is intended to provide firefighters and first responders with additional strength during particularly strenuous tasks.

The exoskeletons from ULS Robotics are being used in industrial applications by several Chinese organisations, which include Daxing International Airport and China Southern Airlines, together with logistics companies, the construction industry and automotive manufacturers. As an example, in 2021, on the construction site for the 110 kV Kaoyuan substation being developed by the Zhejiang Shaoxing Power Supply Company, operators have been using the HEMS-L waist exoskeleton during heavy lifting tasks.

The battery-powered Guardian XO full-body exoskeleton (Figure 9) produced by Sarcos, originally a spin-out from the University of Utah, is effectively a realisation of the Hardiman, made possible by modern-day technology. It arose from an earlier development supported by DARPA and has 24 DOF and amplifies operator strength by a factor of up to 20× allowing users to lift up to 200 pounds (91 kg). It can be equipped with a range of modular and user-selectable end effectors and redundant hardware and software allow passive braking to prevent injury in the event of a total power failure. It is aimed at applications in manufacturing, assembly, construction and warehouse/logistics and in 2020, Delta Air Lines announced that it has partnered with Sarcos to evaluate the Guardian XO in potential applications such as handling freight at Delta Cargo warehouses, moving maintenance components at Delta TechOps or lifting heavy machinery and parts for ground support equipment. A video clip describing the exoskeleton and showing it in use can be viewed at https://delta-a.akamaihd.net/mm/flvmedia/717/m/F/q/mF_qlo53kg4_j175e8tv_h264_9931653K.mp4.

Conclusions

The exoskeleton business is in a highly dynamic state. A concerted research effort involving advanced AI techniques is underway, which seeks to impart exoskeletons with greatly enhanced capabilities, particularly in clinical applications. In
parallel with this, many new companies have been established during the past decade, several of which are exploiting academic research or have been spun out from academic institutions. The majority are targeting applications in the presently dominant clinical sector, although some are developing products for industrial uses. The industrial sector is viewed as a key growth area, but despite the rapidly growing uses of passive, nonrobotic exoskeletons, particularly in the automotive industry, applications remain limited, although many trials are underway. Some real applications exist for robotic gloves, upper-body, waist and lower-body devices in the logistics, construction, automotive and other industries, but industrial applications for full-body exoskeletons are yet to progress beyond the trial stage.

References


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