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The Use of Lower Limb Exoskeletons to Reduce Load During Orthopedic Surgeries

Catarina Santos[1], Ana Teresa Gabriel[1,2], Cláudia Quaresma[3,4], and Isabel L. Nunes[1,2]

[1]UNIDEMI, Department of Mechanical and Industrial Engineering, NOVA School of Sciences and Technology, Universidade Nova de Lisboa 2829–516 Caparica, Portugal
[2]Laboratório Associado de Sistemas Inteligentes, LASI, 4800–058 Guimarães, Portugal
[3]Physics Department, NOVA School of Science and Technology – FCT NOVA, Universidade Nova de Lisboa, 2829–516 Caparica, Portugal
[4]LIBPhys-UNL, Physics Department, NOVA School of Science and Technology FCT NOVA, Universidade Nova de Lisboa, 2829–516 Caparica, Portugal

ABSTRACT

During orthopedic surgeries, surgeons have to operate for long hours in a standing position, performing repetitive and/or forceful movements, and operating in sustained awkward postures, which raises the risk of work-related musculoskeletal disorders (WRMSD). Therefore, it is essential to find solutions that allow to reduce the exposure to risk factors while providing comfort, without affecting concentration during work. Lower limb exoskeletons can be considered an innovative assistance solution that helps workers perform their tasks by supporting the musculoskeletal system. Lower limb exoskeletons are wearable 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 is generally classified as an active or passive system, adding strength to the wearer. Therefore, these devices can be an opportunity to reduce muscular, joint, ligament, and bone stress at work, and potentially prevent WRMSD by physically assisting surgeons. Thus, surgical environments need to be improved to reduce the surgeon's physical burden and enhance the quality of surgery. On that account, the main goals of this paper are: 1) to provide an overview of the risk factors related to the development of lower limb WRMSD, which are presented in orthopedic surgeries; 2) to explain how adopting lower limb exoskeletons might reduce the load experienced in the lower limbs; 3) identify current roles of existing lower limb exoskeletons; and 4) identify user needs and solutions requirements for future lower limb exoskeleton to be implemented in orthopedic surgery rooms.

Keywords: Wearable devices, Lower limbs, Orthopedic surgery, Work-related musculoskeletal disorders

INTRODUCTION

Work-related musculoskeletal disorders (WRMSD) are increasingly being reported and studied in various occupations worldwide. WRMSD entails a wide range of inflammatory and degenerative conditions which affect muscles, tendons, ligaments, joints, peripheral nerves, and related blood vessels. These conditions are related or aggravated by occupational risk factors such as repetition, force or awkward posture as well as individual and psychosocial risk factors (Punnett and Wegman, 2004; Nunes, 2007, 2009).

Orthopedic surgery practice is highly demanding, mentally and physically. The high rate of lower limb WRMSD documented in those who work in operating rooms reflects the exposure to occupational hazards during orthopedic surgery (Al-Mohrej et al. 2020; Swank et al. 2022).

A cross-sectional study among 140 orthopedic surgeons reported that 85.4% of surgeons that answered the Nordic Musculoskeletal Questionnaire suffered from musculoskeletal pain, whereby 49.5% reported low back pain, 33.3% pain in the knee, 18.8 % foot/ankle pain, and 4.2% of responders experienced hip and thigh pain (Aljohani, 2020). Another study involving 235 orthopedic surgeons with an average of 20 years of practice also reported lower limb repetitive WRMSD and symptoms. In this study, 32.3 % of surgeons reported low back pain, 8.9 % reported lumbar radiculopathy, 10.2 % reported sciatica, and 10.6 % reported plantar fasciitis (Swank et al. 2022). Besides the effects on the individuals, WRMSD can impact on the overall healthcare sector because of lost workdays, inability to execute some or all procedures, and early retirement (Swank et al. 2022). These have an impact on the capacity of the healthcare sector to provide care, as well as adverse economic impact.

Hence, researchers have been focused on arranging the surgical operating room environment to reduce the surgeon's physical burden, including the use of lower limb exoskeletons (Kawahira et al. 2018). Lower limb exoskeletons are wearable augmentative devices designed to lessen muscular, joint, ligament, and bone stress at work by physically assisting the individuals wearing such devices; thus, contributing to prevent WRMSD (Bär et al. 2021). However, to guarantee acceptance and utilization of the lower limb exoskeletons by orthopedic surgeons, the device must not only be safe, comfortable and useful but, just as importantly, must be desirable to the end user. For this reason, it is advisable to adopt a user-centered design approach. This approach follows an iterative development process in which designers focus on understanding and specifying the context of use and the user's needs and requirements to produce solutions that meet these criteria (ISO/IEC, 2019).

Therefore, the main goal of this article are:

1) provide an overview of the risk factors related to the development of lower limb WRMSD, affecting orthopedic surgeons, in order to understand the needs and challenges of developing and using lower limb exoskeletons;
2) explain how the adoption of lower limb exoskeletons may reduce the load exerted in the lower limbs;
3) identify current roles of existing lower limb exoskeletons; and
4) identify user needs and solutions requirements for future lower limb exoskeletons to be used by orthopedic surgeons.

PHYSICAL EFFORT DURING ORTHOPEDIC SURGERY

Orthopedic surgery is generally a physically demanding surgical activity that exposes the surgeon to prolonged standing, and operating in awkward and sustained body postures (Swank et al. 2022).

Regarding the underlying mechanism for the development of WRMSD, blood pooling in the lower limbs is one of the most frequently cited mechanisms for the negative associations seen with prolonged standing. Epidemiological studies support that prolonged standing can increase hydrostatic venous pressure (Kroeger et al. 2004; Tüchsen et al. 2005). Furthermore, previous work suggested that standing for most of the day causes static muscle contraction, especially in the legs and back, which compromises the function of the calf muscle (Krijnen et al. 1998). The diminished calf muscle function may contribute to venous stasis and increased lower limb volume (Seo et al. 1996; Tüchsen et al. 2005; Antle et al. 2013).

Halim and colleagues also noted that prolonged standing and the lack of variation in movement in an upright position may lead to lower back and leg discomfort, which can be linked to muscle fatigue (Halim et al. 2012).

Thus, many studies on occupations requiring a standing position have reported the importance of the duration of standing, working posture, muscle effort, and holding time conditions in the development of lower limb WRMSD (Meijsen and Knibbe, 2007; Mohseni-Bandpei et al. 2011; Halim and Omar, 2012; Aitchison et al. 2016; Awosan et al. 2017). Workers who perform tasks in standing positions are substantially more likely to experience discomfort and muscular fatigue due to the aforementioned risk factors.

Ideally, the WRMSD risk factors should be eliminated or mitigated through the adoption of intervention strategies, such as using lower limb exoskeletons. These wearable devices can support the user by reducing muscular, joint, ligament, and bone stress at work, and potentially prevent the occurrence of WRMSD. The design of these devices needs to provide comfort, prevent muscular fatigue due to the work posture, without affecting the work focus. Therefore, some rules need to be taken into account when it comes to body postures while working, such as: alternating between sitting and standing; and avoiding awkward body postures.

THE USE OF LOWER LIMB EXOSKELETONS TO ASSIST ORTHOPEDIC SURGEONS

Lower limb exoskeletons are wearable mechatronic or mechanical equipment designed as augmentation tools that combine with the user's motions to offer structural support or physical help. Examples of activities benefiting from this augmentation capability involve military, industrial, and medical applications (Bär et al. 2021; Santos et al. 2022).

In general, lower limb exoskeletons are classified into active, passive, or hybrid, depending on the use of a power supply to support its functionalities. Thus, active lower limb exoskeletons use actuators (mechanical drive components) to alter internal or external forces acting on the body in order to sustain or increase the user's strength. These devices can support wearers in tasks involving, for instance, manual handling of heavy workloads (Wei et al. 2020).

On the other hand, passive lower limb exoskeletons can still sustain human movements and reduce discomfort and fatigue by using the restoring forces of springs, dampers, or other materials. These lower limb exoskeletons, such as chairless chairs, can reduce repeated stress resulting from long standing periods or the adoption of awkward postures (Luger et al. 2019).

Lastly, hybrid devices combine two or more technologies to power the exoskeleton, e.g., electrical actuators and mechanical systems.

Concerning the applications of these lower limb exoskeletons to assist surgeons, Kawahira and colleagues designed a chairless chair type of passive lower-body exoskeleton, named Archelis, to reduce the burden on the lower back (namely at the iliopsoas muscle)of surgeons performing laparoscopic surgery in a standing position. The results of the assessment in clinical environment show that muscle activity reduces in the surgery while wearing Archelis (Kawahira et al. 2018). Still, until now, a lower limb exoskeleton was not designed to fill out the needs and to reduce the lower limb's burden associated with prolonged standing specific to orthopedic surgery.

Besides, while lower limb exoskeletons, which focus on reducing lower limb effort, are used in the industrial sector, there are no findings of their application in the healthcare sector. However, several articles have identified common risk factors for developing lower limb WRMSD in surgical and industrial settings (Alaqeel and Tanzer, 2020). For this reason, this article will discuss some exoskeletons already developed for the industry that might also be helpful to assist orthopedic physicians. Table 1 presents the description of some lower limb exoskeletons designed to support standing work and static postures in industrial tasks, and the benefits and hazards reported by the study authors.

As shown in Table 1, there are some studies focused on wearable chairs (Zhu et al. 2018; Li et al. 2019; Luger et al. 2019; Pillai, Van Engelhoven and Kazerooni, 2020; Du et al. 2021; Wang et al. 2021; Tu et al. 2022). Wearable exoskeleton chairs have segments and joints that match those of the person using them. The exoskeleton chair can be carried along and may provide a comfortable seat. Devices, such as Chairless chair, LegX, and the lower limb exoskeleton developed by Zhu and colleagues, are unpowered rigid support exoskeletons that can increase the maximum load capacity by distributing the load to the ground through a rigid frame so that the wearer is only directly subjected to a weak load force. Regarding the advantages, these unpowered devices are more lightweight than active exoskeletons because they do not require external power sources, and the users can use them for as long as they choose without worrying about battery charge. These devices do, however, have some drawbacks. One disadvantage is that these devices can only offer the possibility to manually alter the squatting postures to three fixed height levels, which has a significant negative impact on the worker's efficiency, as workers cannot freely adjust the degree of squatting of the exoskeleton according to their needs (Zhu et al. 2018; Luger et al. 2019; Pillai, Van Engelhoven and Kazerooni, 2020). For instance, when workers need different heights than the ones provided by these exoskeletons, this is a major

Table 1. Exoskeletons to support lower limbs.

Study	Device name/ Power/ weight	Task	Muscle groups	Positive Impacts			Negative Impacts
				Muscle activity reduction	Load reduction	Comfort	
(Luger et al. 2019)	Chairless Chair/ Passive/3.8kkg	Standing or Sitting g	GM, VL	25% (GM)	64%	7.9 (1-10)	Affects stabi-lity;Increases VM activity
(Zhu et al. 2018)	Weight-supported exoskeleton/Pas-sive/2 kg	Standing or Sitting	VL, RF, TA, G	14 – 83 %	-	-	Affects balance; Restricts upper body; Discomfort
(Du et al. 2021)	HUST-EC/ Passive/1.5 kg	Prolonged awkward postures	RF, BF, VL, VM, TA, GL	24 – 93 %	54 – 67%	7.1 – 8.1 (1 – 10)	-
(Pillai, Van Engelhoven and Kazerooni, 2020)	LegX Hybrid/3.1 kg	Static and dynamic tasks	Standing or Sitting	TA, RF, ST, GL	22 – 56 % (RF)	-	-
(Tu et al. 2022)	E-LEG/ Passive/ 3 kg	Standing or Sitting	VL, RF, TA, GM	33 –92 %	-	-	Affect the normal gait
(Wang et al. 2021)	Semi-active exoskeleton/ Hybrid/kg	Standing or Sitting	S,VL,VM, G, VI, RF, GLM	36 – 99 %	64 – 66%	-	-
(Li et al. 2019; Wijegunawar-dana et al. 2019)	ChairX/Hybrid/kg	Standing or Sitting	GL, RF, VL, BF, VM	73 – 87 %	-	-	-

Legend: BF - Biceps Femoris; G - Gastrocnemius (the article do not specify whether it is medial, lateral or both sides of gastrocnemius); GL - Gastrocnemius Lateralis; GLM - Gluteus maximus; GM - Gastrocnemius medialis; RF - Rectus femoris; S – Soleus; ST - Semitendinosus; TA - Tibialis Anterior; VI - Vastus intermedius; VL - Vastus lateralis; VM - Vastus Medialis.

drawback. Another problem highlighted in unpowered devices, like Chairless chair and LegX, is user's stability, as the weight has been grounded through the wearer's foot.

To overcome the issue of fixed sitting heights, Tu and colleagues proposed E-LEG, a powered wearable chair with two design elements that make the device smarter and more adjustable (Tu et al. 2022): one is an active tuning mechanism, a squat height adjustment mechanism, made out of a pawl connected to a pushpull electromagnet, allowing the exoskeleton joint to lock at a variable height; the other is composed of an inertial sensor and a pressure sensor on the exoskeleton's bottom that may be used to control the exoskeleton using a finite state machine and automatically determine the user's current posture.

To overcome the issue of user's stability, Wijegunawardana and colleagues proposed ChairX, a device to improve stability for the wearer by adding a supportive limb, which assists with two sitting postures (Li et al. 2019; Wijegunawardana et al. 2019): forward-inclined leg and backward-inclined leg. It provides sitting assistance for forward-inclined leg postures for a knee flexion of 0° to 60° and backward-inclined leg postures for a knee flexion of 0° to 45°. The ChairX enables the user to change the seated height and adopt various crouched postures. The supportive limb aids in extending the range of motion, improving stability and comfort, and enhancing work quality.

The studies reported in Table 1 demonstrate that although these devices have different mechanisms, they reduce lower limb muscle effort and the load experienced by the lower limbs during prolonged standing or squatting tasks. Therefore, these devices can be adapted to surgery to relieve the stress and strain induced in the lower limb musculoskeletal system.

DISCUSSION

The results presented in the previous section show that lower limb exoskeletons might be a suitable solution to reduce muscle effort and the risk of developing lower limb WRMSD.

As shown in Table 1, all the devices can effectively reduce lower limb muscle activity, especially of the muscles related to squatting activities and prolonged standing work. Reducing the calf muscle's activity is a critical aspect for orthopedic surgeons because static standing tasks impair the function of the calf muscles. Also, the fact that the user can change between different squatting heights without increasing the lower limb's muscle effort is crucial to avoid prolonged static postures during orthopedic surgeries. Furthermore, some hybrid devices have already overcome the limitations of the passive devices identified, such as the restrictions related to the sitting height levels, which limit users' options, and the problems related to users' stability.

Nevertheless, some gaps still need to be filled to adapt these lower limb devices to user needs. These device gaps include: adaptability – most devices were specifically designed for industrial workers, who perform more dynamic tasks than orthopedic surgeons; adjustability – devices should be adjustable to individual users' anthropometry; stability – devices should ensure users' stability without restricting squatting heights, or other activities that do not involve squatting; and weight – devices should be lightweight. Also, to make the device more adapted to orthopedic surgeons' needs, it should focus on reducing muscle activity of soleus and plantaris muscles, as these muscles are involved in movements observed during orthopedic surgery, such as plantar flexion during extended periods.

Concerning the fact that the device should be adapted to each person's anthropometry, future designs of lower limb exoskeletons should have an adjustable attachment to suit the user's size and joints and consider the anthropometry of both men and women. For instance, the device should consider that women generally have larger hips and thighs, so adjustable hip joints should be included and avoid rigid structures (Han, Liu and Zhang, 2021).

Furthermore, to be widely used, comfort and stability are essential aspects to be considered in the design. When the exoskeleton redistributes forces to the user's body like in the case of Chairless chair and LegX, comfort remains challenging. In order to overcome this issue, some studies highlight the importance of reducing or distributing the pressure of the exoskeleton on the human body to increase comfort and user acceptance (De Rossi et al. 2011). To avoid any pain or potential injuries, researchers should also pay close attention to the pressure points and points of contact between the user and the exoskeleton. In order to reduce the pressure from the device, Yu and colleagues propose a design with a larger moment arm of a soft lower limb exoskeleton to mitigate high-pressure concentration on the knee by distributing the pressure along the length of the thigh and shank (Yu et al. 2019).

Regarding mechanical aspects, lower limb devices that meet the needs of surgeons must be kinematically compatible to enable not just squatting tasks, but also other motions typically performed during orthopedic surgeries, such as twisting, forward-leaning, lateral leaning, and plantar flexion; therefore, rigid structures should be avoided in exoskeleton design as they are more likely to limit the range of motion (Meng et al. 2022). However, it is crucial to consider that softer materials have a limited ability to redistribute forces on the user's body since they lack a rigid frame. For instance, plastic components can be used instead of metal structures, which might make twisting motions easier. Furthermore, instead of being task-specific, the design of the exoskeleton should introduce programming to control its degrees of freedom so that the device can fit a more extensive range of tasks without compromising user's stability or overloading muscles that are not involved in the task (Souza et al. 2016).

Additionally, to promote surgeon's acceptance, it is essential to guarantee that the device is lightweight, which is more likely in passive devices as they do not have motors. However, considering the need to provide a device that does not constrict the surgeon's tasks, it might be relevant to integrate sensors that enable, for instance, a stepless sitting posture so that surgeons can choose the position most adapted to the patient being operated on. Furthermore, considering the asepsis requirements in surgical rooms, the components of exoskeletons, including any actuator, should be removable to enable easy disinfection.

In summary, taking into account the identified user needs and the review of available exoskeletons, it is important to consider some requirements when designing a lower limb exoskeleton for orthopedic surgeons. The device should be:

- Adaptable to user needs;
- Adjustable to user's anthropometry;
- Lightweight;
- Easy to put on and take off;
- Not restrictive of upper body motions (e.g., twisting and bending);
- Built using sustainable and easy to disinfect materials.

CONCLUSION

In orthopedic surgery, the use of lower limb exoskeletons has the potential to significantly reduce muscle effort and the risk of developing lower limb WRMSD. Also, improving the working conditions for surgeons will effectively enhance the quality of surgery and benefit patients. Previous publications have also endorsed the use of lower limb exoskeletons to facilitate human tasks in various contexts, such as the industrial environment. However, the user needs and the requirements for the development of exoskeletons for industrial context differ from those required by surgeons.

This paper highlighted some of the physical risk factors contributing to the occurrence of WRMSD in orthopedic surgeons; analyzed the pros and cons of several existent lower limb exoskeletons; and identified user needs and solutions requirements to consider in the development of a lower limb exoskeleton adapted to be used by orthopedic surgeons.

In summary, lower limb exoskeletons adapted to orthopedic surgeons needs can contribute to reducing load during surgery and reducing the risk of developing lower limb WRMSD.

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REFERENCES

Aitchison, Lucy. Cui, Cathy. Arnold, Amy. Nesbitt-Hawes, Erin and Abbott, Jason. (2016). The ergonomics of laparoscopic surgery: a quantitative study of the time and motion of laparoscopic surgeons in live surgical environments, SURGICAL ENDOSCOPY Volume 30 No. 11.

Alaqeel, Motaz and Tanzer, Michael. (2020). Improving ergonomics in the operating room for orthopaedic surgeons in order to reduce work-related musculoskeletal injuries. ANNALS OF MEDICINE AND SURGERY Volume 56.

Aljohani, Linah. Batayyib, Sultan. Ghabban, Khaled. Koshok, Meshal and Alshammari, Abdulmuhsen. (2020). Prevalence of Musculoskeletal Pain among Orthopedic Surgeons in North West Region of Saudi Arabia: A Cross-Sectional Study. JOURNAL OF ORTHOPEDIC RESEARCH & PHYSIOTHERAPY Volume 6 No. 1.

Al-Mohrej, Omar. Elshaer, Amani. Al-Dakhil, Sahar. Sayed, AlBraa. Aljohar, Seham. AlFattani, Areej and Alhussainan, Thamer. (2020). Work-related musculoskeletal disorders among Saudi orthopedic surgeons: a cross-sectional study BONE & JOINT OPEN Volume 1 No. 4.

Antle, David. Vézina, Nicole. Messing, Karen and Côté, Julie. (2013). Development of discomfort and vascular and muscular changes during a prolonged standing task. OCCUPATIONAL ERGONOMICS Volume 11 No. 1.

Awosan, Kehinde. Yikawe, Semen. Oche, Oche and Oboirien, Muhammad. (2017). Prevalence, perception and correlates of low back pain among healthcare workers in tertiary health institutions in Sokoto, Nigeria. GHANA MEDICAL JOURNAL Volume 51 No. 4.

Bär, Mona. Steinhilber, Benjamin. Rieger, Monika and Luger, Tessy. (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 Volume 94.

De Rossi, Stefano. Vitiello, Nicola. Lenzi, Tommaso. Ronsse, Renaud. Koopman, Bram. Persichetti, Alessandro. Vecchi, Fabrizio. Ijspeert, Auke. Van der Kooij, Herman and Carrozza, Maria. (2010). Sensing Pressure Distribution on a Lower-Limb Exoskeleton Physical Human-Machine Interface. SENSORS Volume 11 No. 1.

Du, Zihao. Yan, Zefeng. Huang, Tiantian. Bai, Ou. Huang, Qin and Han, Bin. (2021). Mechanical Design with Experimental Verification of a Lightweight Exoskeleton Chair. JOURNAL OF BIONIC ENGINEERING Volume 18 No. 2.

Halim, Isa and Omar, Abdul. (2012). Development of Prolonged Standing Strain Index to Quantify Risk Levels of Standing Jobs. INTERNATIONAL JOURNAL OF OCCUPATIONAL SAFETY AND ERGONOMICS Volume 18 No. 1.

Halim, Isa. Omar, Abdul. Saman, Alias and Othman, Ibrahim. (2012). Assessment of Muscle Fatigue Associated with Prolonged Standing in the Workplace. SAFETY AND HEALTH AT WORK Volume 3 No. 1.

Han, Yibo. Liu, Ying and Zhang, Wuxiang. (2021) “Design of a Passive Exoskeleton Chair with an Auxiliary Support Mechanism for Assembly Tasks”, proceedings of the IEEE International Conference on Robotics and Biomimetics (ROBIO), Sanya, China.

ISO - International Organization for Standardization (2019). ISO 9241-210:2019. ISO Website: https://www.iso.org/standard/77520.html.

Kawahira, Hiroshi. Nakamura, Ryoichi. Shimomura, Yoshihiro. Oshiro, Takashi and Okazumi, Shinichi. (2018). Clinical Use of a Wearable Lower Limb Support Device for Surgeries Involving Long Periods of Standing. JOURNAL OF JAPAN SOCIETY OF COMPUTER AIDED SURGERY Volume 20 No. 3.

Krijnen, R. Boer, E. M. Ader, H. J. and Bruynzeel, D. P. (1998). Diurnal volume changes of the lower legs in healthy males with a profession that requires standing. SKIN RESEARCH AND TECHNOLOGY Volume 4 No. 1.

Kroeger, K. Ose, C. Rudofsky, G. Roesener, J. and Hirche, H. (2004). Risk factors for varicose veins. INTERNATIONAL ANGIOLOGY: A JOURNAL OF THE INTERNATIONAL UNION OF ANGIOLOGY Volume 23 No. 1.

Li, Zhiyuan. Zhang, Tao. Xue, Tao. Du, Zihao and Bai, Ou. (2019) “Effect evaluation of a wearable exoskeleton chair based on surface EMG”, proceedings of the Chinese Control Conference (CCC), Guangzhou, China.

Luger, Tessy. Seibt, Robert. Cobb, Timothy. Rieger, Monika and Steinhilber, Benjamin. (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 Volume 80.

Meijsen, Paul and Knibbe, Hanneke. (2007). Prolonged Standing in the OR: A Dutch Research Study. AORN JOURNAL Volume 86 No. 3.

Meng, Qiaoling. Zeng, Qingxin. Xie, Qiaolian. Fei, Cuizhi. Kong, Bolei. Lu, Xuhua. Wang, Haibin and Yu, Hongliu. (2022). Flexible lower limb exoskeleton systems: A review. NEUROREHABILITATION Volume 50 No. 4.

Mohseni-Bandpei, Mohammad. Ahmad-Shirvani, Marjan. Golbabaei, Nazanin. Behtash, Hamid. Shahinfar, Zahra and Fernández-de-las-Peñas, César. (2011). Prevalence and Risk Factors Associated with Low Back Pain in Iranian Surgeons. JOURNAL OF MANIPULATIVE AND PHYSIOLOGICAL THERAPEUTICS Volume 34 No. 6.

Nunes, Isabel L. (2007). Knowledge acquisition for the development of an upper-body work-related musculoskeletal disorders analysis tool. HUMAN FACTORS AND ERGONOMICS IN MANUFACTURING Volume 17 No. 2.

Nunes, Isabel L. (2009). FAST ERGO_X – A tool for ergonomic auditing and work-related musculoskeletal disorders prevention. WORK Volume 34 No. 2.

Pillai, Minerva. Van Engelhoven, Logan and Kazerooni, Homayoon. (2020). Evaluation of a Lower Leg Support Exoskeleton on Floor and Below Hip Height Panel Work. HUMAN FACTORS: THE JOURNAL OF THE HUMAN FACTORS AND ERGONOMICS SOCIETY Volume 62 No. 3.

Punnett, Laura. and Wegman, David. (2004). Work-related musculoskeletal disorders: the epidemiologic evidence and the debate. JOURNAL OF ELECTROMYOGRAPHY AND KINESIOLOGY Volume 14 No. 1.

Santos, Catarina. Gabriel, Ana. Quaresma, Cláudia and Nunes, Isabel L. (2022). Lower limb exoskeletons some examples of application. In: Isabel L. Nunes (eds) Human Factors and Systems Interaction. AHFE (2022) International Conference. AHFE Open Access, vol 52. AHFE International, USA.

Seo, Akihiko. Kakehashi, Masayuki. Tsuru, Satoko and Yoshinaga, Fumitaka. (1996). Leg Swelling during Continuous Standing and Sitting Work without Restricting Leg Movement. JOURNAL OF OCCUPATIONAL HEALTH Volume 38 No. 4.

Souza, Rafael. Sanfilippo, Filippo. Silva, José and Cordero, Arturo. (2016) "Modular exoskeleton design: Requirement engineering with KAOS", proceedings of the 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), Singapore.

Swank, Katherine. Furness, Jamie. Baker, Erin. Gehrke, Corinn and Rohde, Rachel. (2022). A Survey of Musculoskeletal Disorders in the Orthopaedic Surgeon: Identifying Injuries, Exacerbating Workplace Factors, and Treatment Patterns in the Orthopaedic Community. JAAOS: GLOBAL RESEARCH AND REVIEWS Volume 6 No. 5.

Tu, Yao. Zhu, Aibin. Song, Jiyuan. Zhang, Xiaodong and Cao, Guangzhong. (2022). Design and Experimental Evaluation of a Lower-Limb Exoskeleton for Assisting Workers With Motorized Tuning of Squat Heights. IEEE TRANSACTIONS ON NEURAL SYSTEMS AND REHABILITATION ENGINEERING Volume 30.

Tuchsen, F. Hannerz, H. and Krause, N. (2005). Prolonged standing at work and hospitalisation due to varicose veins: a 12 year prospective study of the Danish population. OCCUPATIONAL AND ENVIRONMENTAL MEDICINE Volume 62 No. 12.

Wang, Zhuo. Wu, Xinyu. Zhang, Yu. Chen, Chunjie. Liu, Shoubin. Liu, Yida. Peng, Ansi and Ma, Yue. (2021). A Semi-active Exoskeleton Based on EMGs Reduces Muscle Fatigue When Squatting. FRONTIERS IN NEUROROBOTICS Volume 15.

Wei, Wei. Zha, Shijia. Xia, Yuxuian. Gu, Jihua and Lin, Xichua. (2020). A Hip Active Assisted Exoskeleton That Assists the Semi-Squat Lifting. APPLIED SCIENCES Volume 10 No. 7.

Wijegunawardana, I. D., Kumara, M. B. K., De Silva, H. H. M. J., Viduranga, P. K. P., Ranaweera, R. K. P. S., Gopura, R. A. R. C. and Madusanka, D. G. K. (2019) "ChairX: A robotic exoskeleton chair for industrial workers", in proceedings of the 16th International Conference on Rehabilitation Robotics (ICORR), Toronto, ON, Canada.

Yu, Shuangyue. Huang, Tzu-Hao. Wang, Dianpeng. Lynn, Brian. Sayd, Dina. Silivanov, Viktor. Park, Young. Tian, Yingli and Su, Hao. (2019). Design and Control of a High-Torque and Highly Backdrivable Hybrid Soft Exoskeleton for Knee Injury Prevention during Squatting. IEEE ROBOTICS AND AUTOMATION LETTERS Volume 4 No. 4.

Zhu, Aibin. Shen, Zhitao. Shen, Huang. Wu, Hongling and Zhang, Xiaodong. (2018) "Design of a Passive Weight-Support Exoskeleton of Human-Machine Multi-Link", proceedings of the 15th International Conference on Ubiquitous Robots, Honolulu, HI, USA.