An Ergonomic Overview on Exoskeletons, Orthosis, and Prosthesis: Potential Impacts and Future Research Directions

Abstract

For over 100 years, researchers and inventors have attempted to create devices that work in parallel with the body's muscles and tendons in order to augment them. The potential impact of recent Exoskeleton technology on decreasing Work Related Musculoskeletal Disorder (WMSD) injuries and their associated reduction of monetary costs is encouraging. With any new technology however, there are potential user risks involved with bionic exoskeletons that need to be addressed, specifically physical ergonomic and psychological human factor risks. This paper offers an overview on ergonomic risks on the future use of exoskeletons in an industrial environment. It provides exoskeleton background, discusses orthotic ergonomic risks that parallel exoskeleton ergonomic risk factors, and considers exoskeleton psychological human factor risks.

At the early stage of this budding multi-billion dollar industry (Quinn, J., 2015), the time to make necessary exoskeleton design changes, based on scientific/medical research, is now. However, until standards are written and testing completed, the traditional method of employing a Hierarchy of Controls method should be used to mitigate industrial WMSD risk.

Keywords: exoskeleton, industrial, musculoskeletal, ergonomic, WMSD

An Ergonomic Overview on Exoskeletons, Orthosis, and Prosthesis: Potential Impacts and Future Research Directions

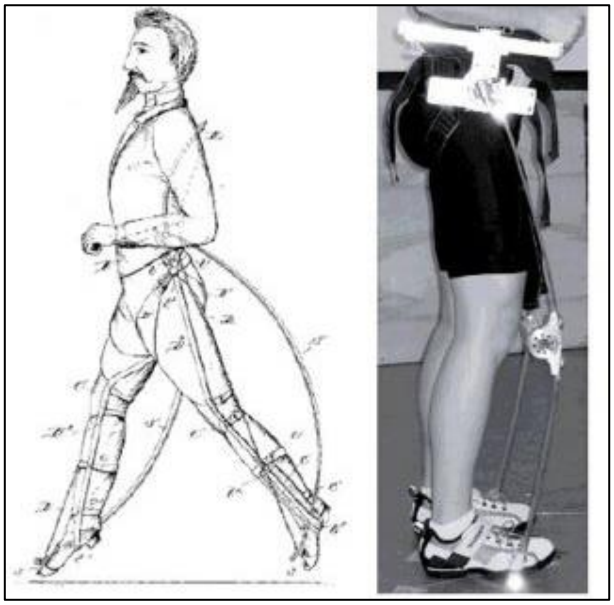
For centuries, people have been faced with the challenge of caring for the injured and maimed, with missing limbs and/or musculoskeletal and neuromuscular injuries (Georgia Tech, 2018). This has led to the solutions of prosthetics and orthosis. Yet scientific research into human locomotion, biomechanics, and the development of new materials have been applied towards creating improved solutions (including prosthetics, orthoses, and now exoskeletons) only within the past 100 years. Recently, this undertaking's success has led to a situation described in an article by Quinn entitled <u>Global Exoskeleton Robot Market Size at $16.5 Million will Reach $2.1 Billion by End of 2021</u> (2015):

> "Global Exoskeleton Market Shares, Strategy, and Forecasts, Worldwide, 2015 to 2021 are poised to achieve significant growth as the exoskeletons are used inside rehabilitation treatment centers and at home to provide stability for paraplegics and people who need gait training. Ultimately, exoskeletons will be used for the rehabilitation of all patients with serious physical injuries or physical dysfunction." (p. 1)

The pursuit of solutions to bodily injury and enhanced healing has long paralleled the desire to augment or increase the healthy body's strength and endurance. (Herr, 2009, p.1) The same products of the latest medical research have been applied to completing work tasks, rather than as solutions for those suffering injury. This has blurred the lines between traditional medical prosthetics, medical orthosis, and newer bionic exoskeletons either powered, unpowered, or a hybrid of the two.

Background

The inventor Nicholas Yagn of St. Petersburg, Russia, patented earliest known exoskeleton in 1890 for a device he called an “Apparatus for facilitating walking” (Yagn, 1890) (Figure 1). This design utilized a giant bow spring as an energy source to facilitate leg movement. Later designs utilized gasbags to store energy. The earliest powered exoskeleton was in 1919 (Kelley, 1919). Called the Pedomotor, this design also was to facilitate walking. As an external power source, this device utilized a small steam engine worn on the user’s back. Although neither device was actually completed, an unpowered design similar to Yagn’s was improved and built by the MIT Biomechanics Group in 2006 (Figure 2.). The improvements focused on reducing the metabolic power needed by the user, succeeding by an average of 24% in performing the task of hopping (the biomechanics of hopping are similar to running). (Herr, 2009, p.3).



Figures 1, 2. Exoskeletons that act in parallel with the human lower limb for load transfer to the ground. Examples are Yagn's running aid [left], MIT's hopping exoskeleton [right]. Photo from Herr, H. 2009. Exoskeletons and orthoses: classification, design challenges and future directions.

Compare Yagn/MIT’s small, unpowered design (called a “passive” exoskeleton) with a design the public thinks about when the word “exoskeleton’ is used: a powered or “active” exoskeleton. The Human Universal Load Carrier (HULC) (Figure 3) was a 2010 design utilizing a large metal frame, multiple electric motors and batteries as an external power source. Both designs accomplished to varying degrees the goal of lowering the users metabolic cost, however the HULC was ultimately unsuccessful because of its size and power consumption. (Marinov, 2016) The Yagn/MIT design conversely worked because of its lighter weight and better human/user interface.

Figure 3. The Lockheed HULC. Photo courtesy of Lockheed-Martin.

Bionic Exoskeletons and Metabolic Cost

The primary goal for bionic exoskeleton design and function should be to reduce the amount of the user’s energy used (or metabolic cost) when performing a given work task using an exoskeleton compared to not using one at all. Regardless of the functional goal of an exoskeleton, minimizing the user’s metabolic costs while wearing the device is crucial. According to Ferris, Sawicki, and Daley (2007):

> “Body mechanics do not relate directly with metabolic energy use. Muscle tissue requires metabolic energy to develop force. The total energy consumption depends on both the force and work performed during the (user’s muscle) contraction.”

In other words, the metabolic cost that a user pays when performing a task not only consists of how much muscle force/contraction a person uses during the task (a *concentric* contraction). Additionally, it is also how often during a task their muscles perform controlled lengthening contractions (an *eccentric* contraction), and how many times their muscles are forcefully tensed, without significantly changing length, to maintain a static posture (an *isometric* contraction). All of these use metabolic energy. Engineers mistakenly assume that replacing a muscle's force output (for example, a bicep muscle's contraction when lifting an extra heavy object) with an electric motor can not only increase the user's strength but make the task of lifting that extra heavy object practical to include in the user's everyday task catalog. Adding the electric motor just increases the user's force output or strength, *not* making their total daylong work easier. Using this strategy, at the end to the day the user will have still have paid almost as much metabolic cost as not using an exoskeleton and be just as tired, if not more so.

Methodologies for measuring metabolic cost while using an exoskeleton are currently under discussion. There are traditional methods of measuring metabolic cost, such as direct calorimetry, indirect calorimetry using oxygen analysis, detailed questionnaires, heart rate measurement, etc. Currently one of the most promising methods to predict exoskeleton metabolic impact was developed by Mooney et. al, (2014), using what they call the Augmentation Factor.

Power Consumption

The second goal of bionic exoskeleton design is lower external power consumption by the exoskeleton itself. This is the reason the HULC failed; development had reached a point where it needed more battery power, which increased the total weight of the bionic exoskeleton system, which required more batteries and lager motors to compensate, which increased the weight again, etc. into an endless loop that halted research into the design (Marinov, 2016). Ferris et al. (2007) note: “Reduction of the power demands of robotic exoskeletons will allow smaller, lighter designs that are easier to use and more versatile.” (p. 509)

Discussion

Ergonomic Risks

The Occupational Safety and Health Administration (OSHA) lists seven ergonomic risks that can lead to Musculoskeletal Disorders (MSDs) (Occupational Safety and Health Administration, 2018). Bionic exoskeletons are susceptible to susceptible to six of the seven:

1. **Working in awkward postures or being in the same posture for long periods.** Using positions that place stress on the body, such as prolonged or repetitive reaching above shoulder height, kneeling, squatting, leaning over a counter, using a knife with wrists bent, or twisting the torso while lifting.

Two different risks can be parsed from this:

Working in awkward postures

Humans are notoriously bad at using and maintaining “stressless”, neutral posture even though the human body is able to perform tasks better with less risk of injury. A bionic exoskeleton could be used a “forcing function”, constraining the user into a neutral posture for better biomechanics. For example, the existing Levitate Airframe supports the upper body during tasks, helping to alleviate static muscle contractions as when holding a weighted tool at arm level for an extended period. A side effect of the Airframe is that because the Airframe’s upper arm supports pull the user’s shoulders slightly back, the user finds it impossible to lift an object by bending at the waist: they must keep their back in a neutral upright position and bend at the knees. In their meta-analysis on a Personal Lift-Assist Device (PLAD), de Loose, Bosch, Krause, Stadler, and O’Sullivan (2015), noted an increase in leg muscle activity evident from electromyography (EMG).

> “The increase in leg muscle activity could be explained by the fact that external forces applied by the equipment needs to be counteracted to retain balance, both in static holding and in dynamic lifting activities.” (p. 5)

They also noted, “…subjects were observed changing their lifting technique towards a more squat-like lifting pattern, which might also may be an explanation for higher muscle activity in the leg muscles when wearing a passive exoskeleton.” (p. 5)

There is also a risk for exoskeletons making an individual’s biomechanics worse. The kinesiologist Steindler (1955) defined the concept of kinetic chains as “links of body parts, such as the foot, ankle, knee, and hip. Each link has an effect on the others.” Horbal (2009) discusses a similar situation about foot orthotics that can be applied to exoskeletons:

> “Orthotics have been compared to eyeglasses-they are not designed to cure the problem, but to assist/solve the functional problem, and to help the patient’s foot work better. …However, they are also often misused, and not well thought out in their application… A foot orthosis is a device placed inside a shoe and worn

> underneath the foot that is used to help the foot and lower kinetic chain (LKC) function… Orthotics can be designed to synchronize the mechanics of the LKC by holding the foot as near to its optimal functional position as possible…Biomechanical dysfunction often leads to alterations in weight distribution and overload to the forefoot… These functional anomalies lead to altered functional biomechanics in gait leading to pain."

An individual worker using a bionic exoskeleton may be facing a similar misuse; a bionic exoskeleton may impose forces or constrain motion in such a way that alters the natural movement sequence that the individual has acquired from previous activity.

Working in the same posture for extended periods of time

As mentioned in the above example, the existing Levitate Airframe supports the upper body during tasks, helping to alleviate static muscle contractions as when holding a tool at arm level for an extended period. However, prolonged use of this or any bionic exoskeleton could also increase user muscle weakness. Eisinger, Kumar, and Woodrow (1996) addresses an analogous situation using lumbar orthotics: "Prolonged use of lumbar orthotics may be associated with trunk muscle weakness in the population studied. Prescribers should continue to limit duration of use when possible and to consider strengthening exercises when prolonged use is anticipated." (p.1)

2. **Localized pressure into the body part.** Pressing the body or part of the body (such as the hand) against hard or sharp edges, or using the hand as a hammer.

Workspaces and tools causing harmful contact stress have long been a concern in industrial settings. Surfaces that are too hard or sharp can cause WMSDs if they have excess contact with the body. Orthotic foot inserts and/or compression mats at workplaces have been used successfully to alleviate contact stress from standing on a hard surface. “One of the main issues with using powered exoskeletons is the creation of pressure points and skin damage due to imperfect fit or components sliding across the body creating shear forces.” (Marinov, 2018). To address this concern, designers have used exoskeletons that are anthropometric in nature. According to de Loose et al. (2016):

> “The main advantage (of anthropometric designs) is that the footprint of the exoskeleton is relatively small as it adheres directly to the body, and the movements should in theory be unrestricted… exoskeletons need to apply pressure on the body to function. If not carefully designed these contact areas may experience discomfort and possibly injury, which may lead to user reluctance to use the exoskeleton.” (p. 5, 6)

3. **Vibration.** Both whole body and hand-arm, can cause a number of health effects. Hand-arm vibration can damage small capillaries that supply nutrients and can make hand tools more difficult to control. Hand-arm vibration may cause a worker to lose feeling in the hands and arms resulting in increased force exertion to control hand-powered tools (e.g. hammer drills, portable grinders, chainsaws) in much the same way gloves limit feeling in the hands. The effects

of vibration can damage the body and greatly increase the force which must be exerted for a task.

Ergonomically harmful vibrations take place in the lower hertz range (International Organization for Standardization (ISO) Standard 2631-1, 1997), and express themselves in either Whole-Body Vibration (WBV) or Hand-Arm Vibration (HAV) injuries. If the exoskeleton system has a direct connection to the vibration source (ex. tool), the system could amplify harmful amplitudes. However, the bionic system could be designed to dampen these vibrations. For example, the Marine-Mojo is a passive partial-body exoskeleton that "provides relief from muscle fatigue which decreases the probability of injury and increases the alertness of the crew on small, fast patrol boats." (Marinov, 2015).

Additionally, a worker performing tasks in a non-neutral posture are more susceptible to vibration risks. (Jack, Oliver, 2008). If a worker using bionic exoskeleton is forced into a non-neutral posture by exoskeleton, the user could be more susceptible to vibration-caused injury.

4. **Exerting excessive force.** Examples include lifting heavy objects or people, pushing or pulling heavy loads, manually pouring materials, or maintaining control of equipment or tools.

Excessive force acting on different parts of the body during work tasks has long been a factor in causing WMSDs. Orthotics have been used to reduce weight-bearing forces to a particular body area for recovering patients (Horbal, 2009) as well as able-bodied workers. An example of the latter is using a foot insert to reduce compression stress for workers who need to stand at their workstation for an extended time. Likewise, exoskeletons have the potential to reduce these underlying force factors associated with developing WMSD injuries. (de Looze, et al., 2016)

As stated above, one of the main goals for exoskeletons is to reduce a worker's fatigue and metabolic cost. As Butler states, properly designed exoskeletons empirically accomplish this: "shown in results of Chase's EMG study, the use of an exoskeleton PED (personal ergonomic device) helps to prevent fatigue by slowing muscle contractions that lead to the decline in a muscle's ability to generate force." (Butler, 2016, p. 36). However, the potential for injury that could result though from improperly design exoskeletons that do not reduce the worker's metabolic cost could prove disastrous. More accidents and injuries happen when a person is fatigued; the resulting injuries could be larger than normal workplace accidents due to the increased forces involved in output of a powered, active exoskeleton.

5. **Performing the same or similar tasks repetitively**. Performing the same motion or series of motions continually or frequently for an extended period of time.

"Repetitive lifting fatigues the musculature involved and may lead to an increased risk of injury." (Godwin, Stevenson, Agnew, Twiddy, Abdoli-Eramaki, and Lotz, 2009.) Workers using exoskeletons have been tested in a number of measures (i.e. % MVC, EMG, subjective questioning) and have found that exoskeletons decrease worker fatigue. (de Looze, et al. 2016, p. 16). While exoskeleton use can assist the human body accomplishing repetitive motions without injury, particularly passive designs, the amount of time a worker spends in performing these harmful motions could counter-intuitively increase because the user is feeling less pain performing the repetitive motion while using the exoskeleton. Human nature tells the user they can now increase the amount of time doing it. Training specific to repetitive motion risk should accompany exoskeletons used for this purpose.

6. **Combined exposure to several risk factors.** May place workers at a higher risk for MSDs than does exposure to any one risk factor.

This risk is prevalent in the field, and often requires a trained specialist to parse out different risks.

Physiological Risks

One potential associated risk, unrelated to WMSD risk, are potential hot surfaces. Van der Vorm, de Looze, Hadziselimovic, and Heiligensetzer, (2016) commented on this in reporting on the Robo-Mate project for the European Union (Van der Vorm et al., 2016, p. 8, 13). Even if correctly designed however, form-fitting exoskeletons, much like present day military body armor, have the potential to become uncomfortably warm or hot to the wearer. Hot temperatures can cause decreased blood flow going to the active muscles and brain leading to fatigue. In their review of the PLAD exoskeleton system, Graham et al. (2009) noted “Several workers also reported that the device was somewhat hot, which had the potential to cause heat strain and reduced productivity with prolonged exposure. A lighter material with vents would go a long way in increasing user comfort." (p. 110)

Human Factor Psychological Risks.

There are two foreseeable human factor associated risks involved with using an exoskeleton. The first is an overconfidence effect. This is a well-established bias in psychology, in which a person's subjective confidence in his or her judgements is reliably greater than the objective accuracy of those judgements. (Pallier, Wilkinson, Danthiir, Kleitman, Knezevic, Stanko & Roberts, 2002). After working with an exoskeleton, a user's perception of their strength and endurance will be altered. This phenomenon was mentioned in Hugh Herr's TED talk on exoskeletons: non-disabled test subjects mentioned that after using the exoskeleton their existing biological legs felt "ridiculously heavy and awkward" compared to when they had the exoskeleton on. (Herr, 2016). Someone attempting a task immediately after using an exoskeleton, if they are not conscious that they no longer have the augmented system, could be vulnerable to an overexertion injury or accident.

The second risk is choosing to use an exoskeleton in the first place. As stated above exoskeletons have the potential to help prevent injury and reduce costs, yet if the usability is not high and it does not easily fit into a worker's everyday routine, the exoskeleton will not be used: . "…Minimization of the metabolic energy expenditure will improve device usability." (Farris, et al., 2007, p. 508). Workers generally want to come into their job in the morning, put on the exoskeleton, and forget about it for the rest of the day. Speaking on website usability, Jakob Neilsen of the Neilsen Norman Group (Neilsen 2012) states:

> “If a website is difficult to use, people leave. If the homepage fails to clearly state what a company offers and what users can do on the site, people leave. If users get lost on a website, they leave. If a website's information is hard to read or doesn't answer users' key questions, they leave. Note a pattern here?”

This is true about usability in general, not just websites; it will not become part of the human/machine system it if it is difficult to use no matter if it is a tool, personal protective equipment, or piece of electronics. The usability of an exoskeleton’s human-machine interface critical for user acceptance and everyday use.

Conclusion

The application of scientific research been applied into human locomotion, biomechanics, and the development of new materials and devices has blurred lines between prosthetics, used for persons missing limbs, orthoses, a device used to assist a person with a limb pathology, and an exoskeleton, used augment the performance of an able-bodied person. Bionic exoskeletons used for industrial purposes have the potential to have a major positive impact on occupational health. The workforce in the United States is aging (Bureau of Labor Statistics, 2014); bionics could be used as an aid for those aging workers to keep them physically at their jobs. (Butler, 2016, p.33, 36). The disabled using bionic exoskeletons as advanced prosthetics could lead to a greater number occupational opportunities. Able-bodied workers, as well as the aging and disabled, could use bionic exoskeletons to enhance their performance and endurance.

With any new technology, there are potential user risks involved that need to be addressed, specifically physical ergonomic and psychological human factor risks. Lowering user’s metabolic costs while using an exoskeleton should be the number 1 goal of exoskeleton design: doing otherwise invites a host of potential musculoskeletal problems and injuries to the user. Additionally, the human/machine interface (i.e. the individual fit and feel) of wearing an exoskeleton is of primary concern to its acceptance and usability.

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