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A Review of Commercially Available Exoskeletons' Capabilities

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***Abstract*-- Medical exoskeletons are robotic devices that provide paraplegics with the ability to ambulate again. There are four current market leaders in the industry: REX, by Rex Bionics; ReWalk, by Argo Medical Technologies Ltd; Ekso GT, by Ekso Bionics; and Indego, by Parker Hannifin. A weighted table-based method was used to evaluate the capability of these four devices, which was then compared to their maximum speed. The Ekso GT and the ReWalk devices achieved high speeds but had low capability scores due to their instability and minimal safety features. The REX and Indego devices achieved the highest capability scores but for contrasting reasons; the REX devices are inherently stable but have a slow, static gait, while the Indego device relies on walking aids for stability and achieves a faster speed. Both devices scored high in the safety criteria. It was derived from the results that there is an indirectly proportional relationship between speed and stability, and none of the exoskeletons achieve a balance between the two. This study found that there is an opportunity to enhance the speed, mobility, stability, and cost of medical exoskeletons, which is presented below.**

Keywords—Exoskeletons; REX; ReWalk; Ekso; Indego

I. INTRODUCTION

Paraplegia is typically the result of a spinal cord injury or a neuromuscular disorder and prevents a person from walking. In 2013, the Christopher and Dana Reeve foundation found that, approximately, 1 in 50 people are living with paralysis in the United States (US), a 40% increase from previous studies [1]. Paraplegics face both physiological and psychological problems which stem from unnatural lack of movement and the inability to complete abled-bodied tasks. Medical lower-limb exoskeletons can provide the ability to walk again and the exercise needed to treat the physical problems [2].

There are several medical exoskeletons, such as the ReWalk by Argo [3] and REX by Rex Bionics Ltd [4], that are commercially available for both rehabilitation and personal use. Whilst these can improve mobility and yielding great psychological and physiological benefits, their high cost and lack of insurance funding reduces the market to rehabilitation clinics and high income earners. There is interest for the reduction of exoskeleton costs to expand market shares. Aside from this, medical exoskeletons also require development in mobility, as currently they are restricted to walking on level terrains at a slow pace. Many of these devices do not detect or react to perturbations, which may result in the user falling, instead relying on the use of walking aids, such as crutches, and a trained supervisor to accompany the user constantly.

This paper highlights the crucial development areas in medical exoskeletons. The paper's structure is as follows; Section II presents a review of the state-of-art of commercially available exoskeletons; Section III evaluates Section II's findings via a direct comparison; Section IV discusses this comparison and highlights potential development areas; Section V presents our conclusions and recommendations.

II. LITERATURE REVIEW

In this section, commercially available medical exoskeletons, that either have Food and Drug Association (FDA) approval or the CE (European Conformity) marking, that are designed for aiding the rehabilitation process and enhancing the quality of life for paraplegics have been reviewed. Exoskeletons that are limited to the treadmill, such as the Lokomat [5], have been excluded. Four market leaders have been identified and are described below.

A. REX

Rex Bionics Ltd is a New Zealand company founded in 2007 that produces medical exoskeletons that assist rehabilitation and mobility for those with neurological and spinal injuries. There are two variations of the exoskeleton: REX, which is designed for rehabilitation clinics and so can be adjusted to fit different users; and REX P, which is designed for personal use and is customized to the individual's size. Both devices are sold in Australia and New Zealand and have the CE mark to be purchased in Britain and Europe for approximately \$150,000 NZD. To date, Rex Bionics has not gained approval from the FDA and so, the REX exoskeleton can only be sold in the US to be used by rehabilitation clinics. The devices are suitable for use by patients with spinal cord injury (SCI) levels of up to C4/C5 or with other injuries, such as stroke or multiple sclerosis (MS). There is a weight

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restriction of 100 kg and height restriction of between 1.46 m to 1.95 m [6].

The REX exoskeletons has two doubled-tethered straps for each leg, an abdomen strap, and an upper harness to support the user [4]. Each leg has five degrees of freedom; two for each hip and ankle, and one for each knee, which is actuated by brushed DC motors [7]. The aluminium foot plates, that strap onto the user's shoes, are wide and flat to provide further stability on flat surfaces [4]. The resultant weight is 38 kg [8]. 27 on-board microprocessors, and over 1000 lines of code, control the exoskeleton [4]; the resultant is a continuously-balanced, static gait with a maximum speed of 0.2 kph [7]. Two lithium-polymer batteries power the device for up to 2 hours of continuous walking and, due to its static nature, does not consume power while standing still [8]. The user selects actions via a joystick on one of the arm rests. The exoskeleton can manoeuvre in all directions (forward, backwards, and sideways), pivot turn, ascend and descend stairs, as well as doing exercises to promote mobility, such as lunges [4].

Duncan Clement, the Director of Engineering at Rex Bionics Ltd, explains the safety features of the REX exoskeleton: "A power failure (such as removal of the battery pack when the device is in use) will cause the device to shut down. Due to the stable nature of the walking gait, the REX will remain standing in whatever pose it was in at the point of power failure" [9]. An inclinometer located on the main PCB detects any dramatic changes to the altitude of the device and will therefore cut power before the device is at risk of losing balance. Mr Clement also states that a trained spotter or clinician is needed to accompany the user and that the device should be operated on flat terrain [9].

B. ReWalk

In 2014, the ReWalk exoskeleton by Argo Medical Technologies Ltd, was the first exoskeleton to receive FDA approval for SCI injuries of T4 to L5 [10]. It also has the CE mark, allowing the device to be sold in Europe, and has licensing for the Canadian market [11]. The device has two variations: ReWalk-R for rehabilitation clinics and ReWalk-P for personal use. These are purchased for approximately $70,000 NZD [12]. The rehabilitation device comes with a graphical-user-interface (GUI) that the clinician can use to configure settings and is adjustable to different users, while the personal device is fitted to the one user and no GUI [13]. The devices are designed for users with a height between 1.6 m and 1.9 m and a maximum weight of 100 kg [10].

The exoskeleton is secured to the user via a chest strap, waist strap, and eight leg straps. Shoes are provided by Argo that attach onto the device's foot plate [13]. DC motors actuate the hips and knees, while the ankle is passive, though it has a spring assisted dorsi-flexion to aid with walking on uneven terrain [8]. To initiate each step, the user must shift their body weight forward, triggering the tilt sensor located on the chest strap and a maximum speed of 2.6 kph has been recorded; a wrist controller is used to switch actions (sit, stand, walk, turn) [14]. The battery is located alongside the controller in the backpack and can power continuous walking for over 2 hours [13].

In the event of a power failure or if there is a loss of balance, the exoskeleton will perform a "graceful collapse" resulting in a sitting position. Torque threshold limits are also used to detect if a limb has contacted an obstacle, the exoskeleton then notifies the user and returns the leg to standing position [13].

C. Ekso GT

The Ekso GT exoskeleton was created by the American company, Esko Bionics, in 2011, and received CE Marking Certification in May 2012. In April 2016, it received FDA approval for individuals with hemiplegia due to a stroke, or SCI at levels T4 to L5 [10]. This device is purchased for approximately $120,000 [12]. Users have a height restriction of between 1.58m to 1.88m and a maximum weight restriction of 100kg [10].

Actuation is provided at both hips and knees, and the ankles have a passive spring movement [14]. The user is supported by three straps on each leg and a backpack strapped about their torso, which contains the batteries and controller; the batteries provide four hours of continuous walking [10]. The user is required to use crutches not only for additional support but to also control the device. Pressure sensors in the crutches will trigger the walking and sit/stand actions [15]. The walking speed of the device is approximately 2 kph and has a weight of 23 kg [10]. The clinician can vary the power provided to each leg, depending on the walking ability of the user, via the Smart Assist software [2]. In the event of a power failure the knees of the device lock to keep the user upright [10].

D. Indego

The company, Parker Hannifin, received FDA approval for their exoskeleton, Indego, in February 2016 for individuals with SCI at levels up to T7 for personal use and up to T4 in rehabilitation clinics [16]. The device can be purchased in the US and Europe for $70,000-100,000 [12]. Users need to have a height of between 1.55 m and 1.91 m and a maximum weight of 113 kg [16].

a. b. c. d.

Fig. 1. Market leaders for medical exoskeletons: a. Rex, b. ReWalk, c. Ekso, d. ReWalk

The design of the exoskeleton is modular, with hip, upper-leg, and lower leg segments that are assembled via “quick-connects” [14]; the battery and controller are located in the hip segment [16]. The device’s hips and knees are electronically actuated with passive ankle joints; the resultant walking speed is approximately 2 kph and walking can be powered for 1.5 hours [16]. To control the device, the user leans forward or backwards, which triggers the sit, stand, and walk actions, similar to a Segway [2]. The therapist can alter control settings, such as stride length and gait speed, via a wireless application on their phone or tablet [2].

In the 510k device summary report submitted to the FDA for approval, it is reported that a walking aid, such as crutches is required for stability. The exoskeleton can also detect falling and make the necessary adjustments to mitigate injury to the user and in the event of the power failure the knees lock, similar to the Ekso GT device [16]. The falling detection and adjustment method is not yet publicly available.

III. Comparison

In this section, we identify criteria and present a weighted table-based method for evaluating the previously mentioned exoskeletons.

A. Criteria

The selected criteria are defining features beyond the device’s main functionality of providing the ability to walk and are listed in Table I. These describe three factors: the device’s market, safety, and performance. For the device’s market, price, population, and administrative approvals are the main influences. Price is the determining factor for the exoskeleton’s affordability, population determines the type and level of disability that the exoskeleton caters for, and approvals gained states what countries the exoskeleton can be sold in. Therefore, price has a higher importance than the other two as it affects the entire market.

The safety factor is determined by fall-safety features, balancing method, and maneuverability. The fall-safety features are determined by how the exoskeleton predicts and/or reacts to falling, balancing method is the main method used for stabilizing itself and the user, and maneuverability is based on the directions in which the exoskeleton can move, the different terrains it can traverse, and the mobility of the user’s upper body. Both fall-safety features and balancing method directly mitigates risk of injury to user and so have a higher importance.

The performance related criteria are gait, battery life, and weight. The gait of the exoskeleton is compared to that of an abled-bodied being; since this bridges the gap between paraplegics and abled-bodied beings, it is important. The weight of the exoskeleton, predominantly, affects the transportation of the device and battery life can be compensated for via additional batteries.

B. Method

Three weights are used for the criteria based on the criteria’s importance; these are listed alongside the corresponding criteria in Table I. Each of the four exoskeletons are evaluated against the criteria and given a ranking from best to worst; the best device is given the highest rank of 4, and the worst a rank of 1. Two or more of the exoskeletons may be given the same ranking due to similarities. Each rating is then multiplied by the corresponding criterion weight before being summed for each exoskeleton's final score.

TABLE I. CRITERIA AND WEIGHTING

Criteria	Weighting
(A) Price	3
(B) Fall-Safety	3
(C) Balancing Method	3
(D) Manoeuvrabiltiy	2
(E) Human-like Gait	2
(F) Population	2
(G) Administrative Approvals	2
(H) Weight	1
(I) Battery Life	1

C. Results

Using the weighted table method described in the previous section, we have evaluated the discussed exoskeletons. Table II presents the results in the order of: REX, 56; Indego, 56; ReWalk, 46; and Ekso GT, 44.

TABLE II. WEIGHTED TABLE EVALUATION OF MEDICAL EXOSKELETONS

	Criteria									
	A	***B***	***C***	***D***	***E***	***F***	***G***	***H***	***I***	***TOTAL***
REX	1	3	4	4	1	4	3	1	3	**56**
ReWalk	4	1	1	2	4	2	4	2	3	**46**
Ekso GT	2	2	1	1	4	3	4	3	4	**44**
Indego	3	4	1	3	4	2	4	4	2	**56**
Criteria Weight	*3*	*3*	*3*	*2*	*2*	*2*	*2*	*1*	*1*	

These results, which represent the device's capability, were compared against speed, as we deemed speed to be one of the defining factors for the gap between paraplegics and abled-bodied beings. This is illustrated in Figure 2.

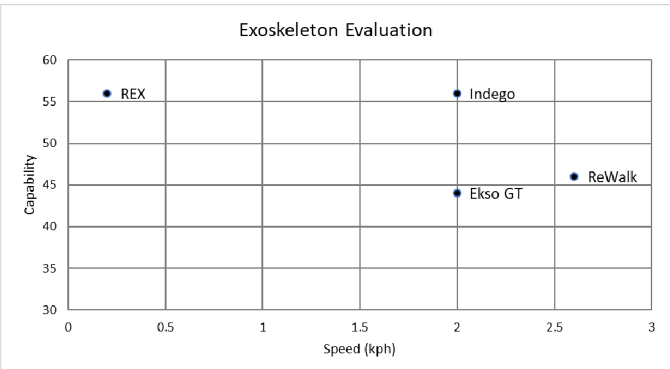

Fig. 2. Comparison of Exoskeleton's Capability and Speed

IV. DISCUSSION

In this section, we discuss each of the identified exoskeletons and their respective score. First, their advantages and disadvantages are discussed; then, their areas of future development are described.

A. Ekso GT

The Ekso GT exoskeleton had the lowest score of 44 due to the combination of a high price and minimal safety features. The major advantage for the Ekso GT is its Smart Assist software which allows the device to be used by a wider range of patients, including hemiplegics, and to greater assist the rehabilitation process by allowing the user to apply their own lower limb strength [17]. Its disadvantages include its reliability on a walking aid for stability; therefore, requiring the user to have upper body strength, which can limit their independence. Figure 2 indicates that the Ekso GT has a relatively high speed, but a low capability score.

B. ReWalk

The ReWalk exoskeleton achieved the next highest score of 46 due to having the lowest price, of $70,000, and a human-like gait. The device also achieves the highest speed of 2.6 kph, which is comparable to the average wheelchair [8]. Its disadvantages include its lack of safety features and stability. The device relies on the use of crutches, limiting the users to people with upper body strength, and the "graceful collapse" reaction to power failure can leave the user in an awkward position until an external person provides help.

C. Indego

The Indego device received the highest score of 56, alongside the REX device. It's speed, lower cost, and safety features are advantageous, notably the fall detection and correction method. Another advantage is its lightweight and modular design, meaning the device can be quickly donned and doffed, easily transported, and compactly stored [14]. The Indego shares the same disadvantage as the ReWalk and Ekso GT, as it relies on crutches for stability, and therefore limits users to those with upper body strength. Figure 2 indicates that the Indego achieves the same speed as the Ekso GT, but has a much higher capability score.

D. REX

The Rex devices also received the highest score of 56 due to its inherently stable nature and mobility. It is the only device, of the four, that doesn't rely on crutches for stability, and the only one that can walk backwards and sideways, increasing the mobility and independence of the user. Not needing crutches means users with more severe disabilities can operate this device, including hemiplegics and tetraplegics [4]. REX's disadvantages include its slow, static gait, which is not human-like, and its limited market due to the high price and lack of FDA approval.

E. Further Improvement Areas

1) Speed vs Stability

In relation to Figure 2 it is clear, from the current four devices, that speed and stability are indirectly proportional to each other. The three exoskeletons that rely on crutches for added stability achieve a faster speed than the self-balancing REX exoskeleton. Further research is required to find a better balance between stability and speed, such as a quicker REX exoskeleton. Achieving a faster walking gait for any of the devices would be desirable, as even the fastest speed of 2.6kph is approximately only half the speed of the average abled-bodied walking male [18].

2) Uneven Terrain

All four exoskeletons are restricted to traversing on smooth surfaces, including grass, with a maximum grade inclination ranging between 1.5 degrees to 5 degrees. To bridge the gap between abled-bodied people and paraplegics, these exoskeletons should be able to transverse over many different terrains, for example: gravel, and soft soil, while remaining stable.

3) Price

The cost of the exoskeletons is currently too high for the personal-use market, with the lowest cost being $70,000. This could be solved by several ways: clinical trials being carried out which could convince insurance companies to cover costs for individuals [19]; or more research into the exoskeleton technologies, with a focus on lowering costs [20]. Until the costs are lowered, it likely that these types of devices will remain in rehabilitation clinics.

V. Conclusions and Recommendations

In this paper, we have discussed the importance of medical exoskeletons and the motivation of this work. Four market leaders in the medical exoskeleton sector have been identified and reviewed. Their capability has been measured using a weighted metric, with results showing two of the exoskeletons: the REX and the Indego, having the same high capability score, though for contrasting reasons. The REX exoskeletons are inherently stable, but are very slow compared to the Indego exoskeleton, which is quicker, but relies on the user using a walking aid for stability. An indirectly proportional relationship between stability and speed is indicated by Figure 2.

This paper recommends that future work should focus on: finding a better balance between stability and speed; increasing the exoskeleton's traversing ability; and decreasing the expense of the devices for individuals.

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