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Comparative study of actuation systems for portable upper limb exoskeletons

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ABSTRACT

During the last two decades, a large variety of upper limb exoskeletons have been developed. Out of these, majority are platform based systems which might be the reason for not being widely adopted for post-stroke rehabilitation. Despite the potential benefits of platform-based exoskeletons as being rugged and reliable, stroke patients prefer to have a portable and user-friendly device that they can take home. However, the types of actuator as well as the actuation mechanism used in the exoskeleton are the inhibiting factors why portable exoskeletons are mostly non-existent for patient use. This paper presents a quantitative analysis of the actuation systems available for developing portable upper arm exoskeletons with their specifications. Finally, it has been concluded from this research that there are not many stand-alone arm exoskeletons which can provide all forms of rehabilitation, therefore, a generic solution has been proposed as the rehabilitation strategy to get best out of the portable arm exoskeletons.

1. Introduction

Stroke is the fourth leading cause of death in the UK. At present, there are over 1.2 million stroke survivors in the UK [1]. According to the Stroke Association, the way of recovery of stroke patients depends on the process of rehabilitation which includes all orthopedic lessons at different phases after stroke [2]. Existing manual therapy has several drawbacks such as the cost of therapy, physical issues from physiotherapy and lack of sufficient number of physiotherapists. Long-term involvement of rehabilitation therapists imposes a huge cost burden. Present annual health and social costs of caring for disabled stroke patients are estimated to be in excess of £5 billion in the UK [3]. The ratio of the number of stroke survivor to the number of experts providing rehabilitation therapy is still not satisfactory. Since the number of people suffering from stroke and different neuromuscular diseases is increasing day by day, the situation is worsening. Also, the duration of training is not adequate due to the fatigue of therapists; patients do not get repetitive and adequate rehabilitation sessions under manual intervention. It is not possible for the patients to receive the recommended amount of medical care from manual therapy [4]. It has been shown that the exoskeleton based rehabilitation can be used as an alternative [5] to regular manual therapy for improving motor function after stroke since the device can be moved in different directions to accommodate all types of exercises [6].

Many exoskeletons have been designed to provide rehabilitation service to post-stroke patients. Based on the structure, exoskeletons can be mainly divided into two categories: ground-based exoskeleton [7] and body-based exoskeleton [8]. The ground-based exoskeletons are attached to a base platform from where full arm motions are controlled. This type of exoskeleton can provide uninterrupted and intensive rehabilitation training to patients. Actuators can be placed at the human joint with structural support from the base [9] or remotely controlled by placing it on the backpack [10]. Most of the ground-based exoskeletons have used brushed or brushless dc motor [11] as their active actuators. Also there are some hydraulic [12–15] and pneumatically powered exoskeletons [16–19] in the market. In the ground-based exoskeleton, motion transferred to the human arm is very stable and the actuator can provide maximum torque to the joint irrespective of the weight of the arm. This type of exoskeleton requires a large space for installation.

In the body based exoskeleton, all mechanical and electronic components including the power supply are placed within the exoskeleton mounted over patient's body and joints can be directly driven by actuators; same as the ground-based system or externally controlled through transmission mechanisms. If the actuator is placed at the joint, the amount of torque required to turn the joint is quite high. To achieve higher joint torque, big and heavy motors are required [20]. As a result, weight as well as size of the exoskeleton could be increased and the structure may not be wearable. Although there are new type of soft actuators

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like pneumatic muscle [21] or flexible fluidic actuators [22] being developed for making portable and lightweight exoskeletons, there are still a number of issues associated with these actuators that make them unsuitable for use on a multi-degree of freedom exoskeletons. The ground-based exoskeletons are suitable for rehabilitation where size and weight of the exoskeleton are not important but for a portable exoskeleton, the actuator should be small and of low weight.

Apart from the structural division of exoskeletons in terms of ground-based and body-based systems, they can also be categorized with respect to their intended applications such as exoskeleton for assistance or therapeutic device for stroke rehabilitation. There are considerable measures of differentiation between these two types of exoskeletons, the assistive exoskeleton is mainly used for providing assistive force to support in activities of daily living or to undertake strenuous tasks. On the other hand, as a therapeutic device, the type and level of external force are varied depending on the post-stroke recovery requirements; it could be assistive or resistive force based for rehabilitation. Besides the health benefits, other design properties are also considered to be significant in this survey which are comforts, ease of putting on/removing the device, purchase cost and energy consumption [23]. On this basis, a simple, user-friendly and affordable system which is lightweight and portable should be the most wanted consideration. Ground-based systems are generally expensive because all the required rehabilitation features are installed into the exoskeleton to accommodate a large variety of patients; mainly suitable for hospitals and health care centres. Such facilities are neither readily available nor affordable for an individual user. Since the ground-based exoskeletons typically use heavy and powerful actuators, the user can't avail the training facility at home or use during travel. This leads to conclude that a mechanically efficient, simple and portable arm exoskeleton is the need for patients requiring rehabilitation therapy post-stroke, so the main aim of this paper is to investigate issues related to actuators and actuation system for developing a portable upper limb exoskeleton.

Although a large number of exoskeletons have been developed and a considerable amount of research has been undertaken, there are hardly any portable upper arm exoskeletons available to the needy user. The main reason for this bottleneck is due to the choice of actuators and the supporting mechanisms for creating a portable device. There are a couple of critical factors which should be integrated into the actuation framework to develop a lightweight exoskeleton. Based on this research the key properties for selecting an actuation system is categorized into four divisions as shown in Fig. 1: the functional activities, technological characteristics, financial benefits and psychological benefits. Out of the four divisions, the first two are crucial. The functional activity defines a standard rehabilitation therapy which not only provides medical benefits but it also guarantees safety and comforts to the users. Patient's prerequisite is to have a user-friendly system which can be effortlessly put-on and taken-off, yet no standard design methodology has been documented to produce portable exoskeletons. However, some design considerations are available to make an actuated device portable. These are; the torque to weight ratio of the exoskeleton should be high enough to carry out the maximum load during exercise. The weight of the system components should be low so that the overall device is wearable and easy to move during therapy exercises. The degree of freedom (DOF) of the exoskeleton is another important factor which should be kept to a minimum to allow minimum number of actuators to be used. Efficient mechanisms should be used for transferring motion from actuator to the joint. In order to actuate the exoskeleton, the battery life is also a very important consideration for providing power to run the exoskeleton for a long time. Besides this, considerations should also be given for the cost of actuators

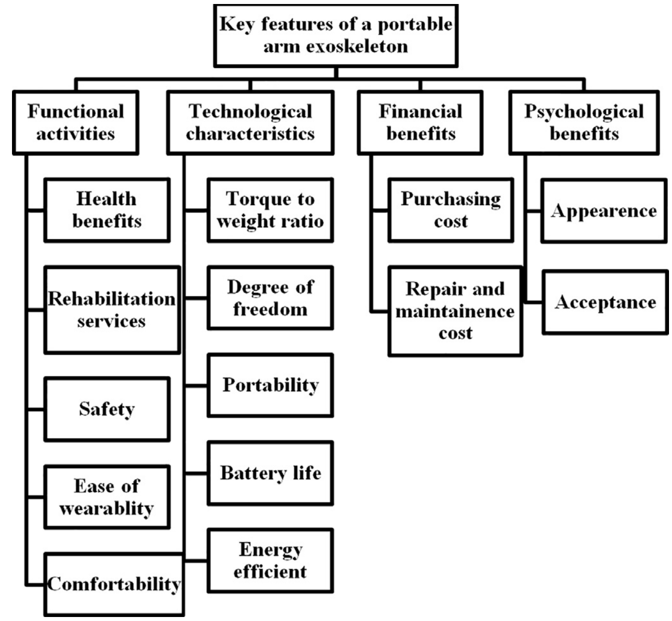

Fig. 1. Key features required for a portable exoskeleton system.

used in the exoskeleton to make rehabilitation a cost-effective therapy compared to the manual treatment and the ease of repair and maintenance should be built into the exoskeleton. Though appearance is least important amongst all the construction parameters of the exoskeleton, it should provide a pleasant and aesthetic look to make it attractive to the patients.

2. Rehabilitation strategy

People suffering from stroke face a lot of physical and psychological problems. Physical inefficiency makes them detached from the social life. According to the standard rehabilitation strategy followed by the healthcare professionals [2], patients have to undergo different modes of exercises from acute phase to the full recovery stage after stroke. The exercises involved in different rehabilitation stages not only aimed to recover their muscle strength but also to get them back into their normal life and improve their mental strength to fit into the social life. Generally, seven standard steps are followed for rehabilitation as developed by the Swedish therapist Brunnstrom [24]. This approach is based on the neurophysiological principles for improving the successive levels of central nervous system (CNS) integration through a synergistic pattern of muscle movement. All these seven stages can be merged into three distinct stages after assessment of the treatment procedure involved in these stages as shown in Fig. 2. The developed exoskeleton should be capable of incorporating all types of exercises required in the three stages. Symptoms in each stage show the sign of recovery. During the acute phase, the joint movement is controlled by applying external force supported by the exoskeleton since there may be spasticity or involuntary movement in the arm. The next phase of recovery shows a better condition where a synergistic pattern in the movement appear as well as spasticity continues to decrease. During this transition, an external supportive force is helpful to implement coordination between the joint movements successfully. This phase of rehabilitation implies a partial control on the movement where patient would commence the motion from their end but assisted by the exoskeleton. The continuous synergistic motion tries to restore muscle strength and reduces the abnormality in the movement which results in a complex coordinated muscle control in the upper arm. In the full recovery stage, patients are able to initiate

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