Proceedings Paper:

Gilson, O, Xie, S orcid.org/0000-0002-8082-9112 and O'Connor, RJ orcid.org/0000-0002-4643-9794 (2022) Design of a Wearable Bilateral Exoskeleton for Arm Stroke Treatment in a Home Environment. In: Proceedings of the 2021 27th International Conference on Mechatronics and Machine Vision in Practice (M2VIP). 2021 27th International Conference on Mechatronics and Machine Vision in Practice (M2VIP), 26-28 Nov 2021, Online. IEEE , pp. 635-640. ISBN 978-1-6654-3154-5

https://doi.org/10.1109/m2vip49856.2021.9665069

Design of a Wearable Bilateral Exoskeleton for Arm Stroke Treatment in a Home Environment

Orla Gilson[1], Shane Xie[2] and Rory J O'Connor[3]

Abstract— **With the number of stroke patients increasing every year, it is important that new ways of approaching rehabilitation are explored. This paper introduces a novel design for a bilateral exoskeleton that aims to allow patients more flexibility in how and where they are able to carry out their rehabilitation. The Bilateral Exoskeleton for Arm Stroke Treatment (BEAST), has been designed for patients to use independently in their own home. The focus of BEAST is to allow therapists to oversee the remote rehabilitation of more patients, effectively reducing waiting times and enabling patients more independence in their recovery process. This paper discusses the design of BEAST, including the kinematics, workspace and torque calculations. It also briefly touches on how the needs of patients can be included in the design and optimisation stages of BEAST.**

I. INTRODUCTION

Stroke is the fourth largest cause of death in the United Kingdom (UK) [1]. It is caused by the interruption of blood flow to the brain. Survivors of a stroke can be left with varying levels of disability depending on the area of the brain affected and the length of time that the blood flow was stopped for. Strokes cause five main types of disability: paralysis or weakness in the muscles; disturbances in the senses; issues using or understanding language; difficulties with memory and thinking; and emotional disturbances [2]. The most common of these is paralysis or weakness, usually in one side of the body in either the arm, leg or face [2]. This side of the body is known as the paretic side, with the other side being the unaffected side.

There are currently over 1.2 million stroke survivors in the UK alone [3]. With 100,000 people suffering from a stroke each year; that's one stroke every five minutes; that number is only going to grow [3]. The methods used for rehabilitation after stroke therefore need to adapt to the growing number of patients. Rehabilitation has the most impact when begun as soon as the patient is stable; sometimes within 24 hours of the stroke occuring; with the best methods of rehabilitation being focused and repetitive movements [2]. Robotic devices would be one of the best options for getting rehabilitation started as soon as possible, as well as being capable of consistent repetitive movements. The current rehabilitation system in place in the UK often has long waiting lists before patients can access therapy after a stroke; causing a detrimental effect to the recovery process. Robotic devices could be used after a short initial assessment to ensure patients are not waiting for long periods of time without any sort of therapy sessions.

Rehabilitation robots were first designed to mimic the movements a therapist would normally work through with a patient. This involved only the paretic limb carrying out exercises. This type of rehabilitation, using only the paretic arm, is known as unilateral training. Bilateral training; carrying out the exercises with both the unaffected and paretic arms; has since become more popular and is accepted by professionals as an effective method of rehabilitation [4][5]. When carried out with an exoskeleton on the paretic arm, the movement of the unaffected arm is tracked and used to control the exoskeleton. Bilateral training uses rehabilitation movements that are similar to the activities of daily living (ADLs). There are six basic ADLs consisting of movement, feeding, dressing, personal hygiene, continence, and toileting; most of which require two hands and a level of coordination that patients may struggle with [6]. These activities are the benchmark for a patient being able to live independently; the end goal for rehabilitation after stroke. There are also two types of bilateral movements; symmetrical, consisting of the two arms moving in either the same direction; shadowing; or in opposite directions; mirroring; and cooperative, consisting of the two arms moving entirely independently of each other.

When a stroke occurs, it can affect a person's dominant side. As a person's dominant arm carries out the majority of the single-handed ADLs, rehabilitation of the dominant side can often be more difficult than if the non-dominant arm is affected. Waller and Whitall discuss how bilateral training can be more effective than unilateral training in this scenario [7]. When the non-dominant arm is affected by stroke, a number of tasks can still be carried out in the same way they were prior to the stroke; such as brushing teeth or writing [7]. However if the dominant arm is affected, many of these tasks need to be relearnt as they often take longer and are more unstable when carried out with the non-dominant arm [7]. Bilateral training is more likely to be effective when the dominant arm has been affected as patients are more likely to have to adjust to using both arms in cooperation to carry out tasks that were previously managed single-handedly [7].

II. BILATERAL EXOSKELETONS

There are many existing bilateral exoskeletons, all of which have different characteristics. These have been condensed into Table I, so that the main design points can be compared. The majority of existing exoskeletons are designed to be used in a hospital environment. Some, such

[1]Orla Gilson is with School of Electronic of Electrical Engineering, University of Leeds, LS2 9JT, Leeds, UK el13og@leeds.ac.uk

[2]Shane Xie is with the School of Electronic and Electrical Engineering, University of Leeds, LS2 9JT, Leeds, UK s.q.xie@leeds.ac.uk

[3]Rory J O'Connor is with the, School of Medicine, University of Leeds, LS2 9JT, Leeds, UK medrjo@leeds.ac.uk

as the fabric based glove [8], and ULERD [9] can also be used in a home environment; but only Omega.7 [10] has been designed solely for home use. The Omega.7 is a table-top grounded exoskeleton that rehabilitates the hand through the use of a haptic interface and motion tracking software [10]. This system requires a number of external systems such as the motion tracking system and a screen, as well as a clear surface to place the device on when in use. These are things that not every household may have access to. BEAST aims to be used in a home environment without any external additions to the system; therefore every patient will be able to use the device no matter what their home may be like.

Many of the existing devices are designed to be wearable, though all of these have been designed for use in the hospital. The existing wearable exoskeletons are actuated through DC motors directly at the joints, such as BRAVO [11], a 2-DOF system for the hand, and BWRD [12], a 1-DOF elbow exoskeleton; or through soft pneumatics, such as the fabric based glove for the hand [8], the master-slave elbow device [13], and the continuum exoskeleton for the shoulder [14]. Soft pneumatics are generally lightweight and therefore can be incorporated into a wearable design very easily. They do however usually need an external reservoir of air, usually a heavy tank or compressor, which can then lead to a partially grounded system.

Perhaps the most closely related exoskeleton to BEAST is the EXO-UL7 [15]. It is also a 7-DOF system for the wrist, elbow, and shoulder; and is based off the cable actuated (CADEN)-7 unilateral exoskeleton [16]. The EXO-UL7 is a prime example of adjusting an existing unilateral exoskeleton to be used in a bilateral system. It uses two of the (CADEN)-7 exoskeletons, one on each arm of the patient. This is not only a costly solution to bilateral training, but also impractical due to the size and weight of two exoskeletons when being worn by the patient; not to mention the footprint of a grounded device such as this in a hospital environment.

Many other exoskeletons were considered during the design phase, mostly unilateral exoskeletons due to the lack of bilateral exoskeletons in literature, but also due to the engineering principles behind them being the same. Alongside the (CADEN)-7, some other notable unilateral exoskeletons researched include CAREX-7 [17], another 7-DOF cable actuated exoskeleton; and ChARMin [18], a 7-DOF modular exoskeleton for use in pediatric rehabilitation; both of which are for the wrist, elbow, and shoulder.

TABLE I: Comparison of Existing Bilateral Exoskeletons

Exoskeleton	Joints (DOFs)	Actuation	Environment	Device
BRAVO [11]	H (2)	DC Motors	Hospital	Wearable
Fabric Based Glove [8]	H (-)	Soft Pneumatics	Home & Hospital	Wearable
Omega.7 [10]	H (7)	Passive	Home	Grounded
Hand-Assist Robot [19]	H (18)	DC Motors	Hospital	Grounded
CyberGrasp [20]	H (5)	Cables	Hospital	Grounded
Robotics Assisted Device [21]	H/W (2)	AC Motors	Hospital	Grounded
Wrist Device [22]	W (2)	DC Motors	Hospital	Grounded
ULERD [9]	W/F/E (3)	Phantom Premium	Home & Hospital	Grounded
EXO-UL7 [15]	W/E/S (7)	DC Motors	Hospital	Grounded
Forearm Device [23]	F (1)	DC Motors	Hospital	Grounded
NTUH-II [24]	F/E/S (8)	DC Motors	Hospital	Grounded
Elbow Device [25]	E (3)	SEA	Hospital	Grounded
BWRD [12]	E (1)	DC Motors	Hospital	Wearable
Master-Slave Device [13]	E (1)	Soft Pneumatics	Hospital	Wearable
Continuum Exoskeleton [14]	S (3)	Soft Pneumatics	Hospital	Wearable

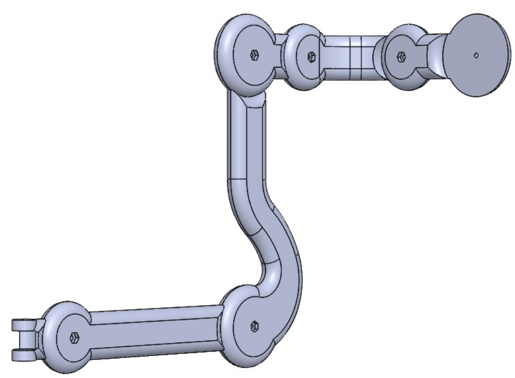

Fig. 1: Initial design of BEAST

III. DESIGN OF BEAST EXOSKELETON

The design of BEAST will be carried out in two stages. This paper discusses the first stage; an initial design from an engineering perspective. The second design stage is the optimisation stage, based on the feedback from a patient needs survey. It was decided that taking an initial design to patients and therapists would gain better feedback. This is because not all participants in the survey will have prior knowledge of exoskeletons and how they work. The initial design is laid out below and can be seen in Fig. 1.

The design specification of BEAST has been created with the aim of designing a wearable bilateral exoskeleton that can be used in a home environment, allowing therapists to reach more patients. This will allow waiting times to be lower and so get patients started on rehabilitation as soon as possible, hopefully resulting in quicker and more successful rehabilitation. Some of the main specification points are shown below:

1) Performance: Full range of motion (ROM), cable actuation system, IMU sensing system, wearable, and bilateral.

2) Environment: In the patient's home, therefore small, compact, lightweight, rechargeable and independent.

3) Maintenance: Regular maintenance carried out between patient use by trained rehabilitation centre staff.

4) Target Product Cost: Low cost to hospitals and patients alike, through low cost components and manufacturing to hospitals, and through deposit or rental schemes to patients.

5) Manufacturing: 3D printing custom link sizes or modular links for customisation.

6) Quality and Reliability: High quality materials, reliable for patients to use at home and easily accessible help and repairs.

7) Installation and Operation: Training sessions for both medical professionals and patients before using the device to ensure safe and successful rehabilitation.

A. Mechanical Design

The initial design focused on meeting the requirements laid out in the specification. The performance of the exoskeleton is centred around the joints, ROM, actuation, and sensing systems. BEAST consists of seven DOFs, focused on the wrist, elbow, and shoulder joints. The shoulder joint of the exoskeleton is capable of three of the human shoulder joints motions; flexion/extension, abduction/adduction, and horizontal abduction/adduction. The elbow joint of the exoskeleton is capable of flexion/extension, and the wrist joint is capable of flexion/extension and radial/ulnar deviation. It was decided not to include the hand at this point due to its individual complexity, requiring at least 14 DOFs in order to actuate each of the fingers. There are also many existing bilateral exoskeletons; such as BRAVO [11], Omega.7 [10], and CyberGrasp [20]; that focus extensively on rehabilitating the individual finger joints.

The shoulder joint of the exoskeleton has two passive DOFs to allow for the movement of the glenohumeral joint. In the human body, the centre of the glenohumeral joint lifts as the arm raises, and so the exoskeleton needs to allow for this movement to maintain the alignment between the exoskeleton and human arm joints. For the elbow joint, it was necessary to create the link with a curve in it to allow for the full ROM. If the link was straight it was only capable of approximately 130°, instead of the full 160°. In the very first sketches of BEAST, a handle was incorporated as the end effector for the patient to grip. During a conversation with a group of therapists it was pointed out that this would actually be detrimental to a patient. This is because after a stroke, a patient can develop spasticity; a condition that causes tightness in the muscles due to prolonged contraction of the muscles, for example when gripping something. Due to this potential condition, the handle of the exoskeleton was removed, in favour of a fabric replacement that can fit around the hand even if patients already have spasticity in the hand.

The links of BEAST are to be 3D printed individually. Using 3D printing allows for several options when it comes to adjusting the size of the exoskeleton to enable it to fit as many patients as possible. This could be done either through custom printing each exoskeleton for the specific patient, or having a set number of sizes of each link that can then be put together in a modular manner. As the joints of the exoskeleton and the human arm need to be aligned, information on the size of the human arm is required. This data has been taken from the 2012 Anthropometric Survey of US Army Personel [26]. Table II contains the relevant data from the survey which can then be used to determine the different sizes of exoskeleton needed.

Each human body is different, from the size of the arm, to the ROM of each joint. The generally accepted ROM of each arm joint is shown in Table III and have been taken from two sources to ensure they are as accurate as possible [27][28]. These are the values that have been used when designing BEAST and when carrying out the kinematics and workspace calculations in the following sections.

B. Kinematic Analysis

For an exoskeleton to be effective in rehabilitation, it must be capable of the full ROM of the human arm. To check that the exoskeleton can carry out all of the necessary movements and does not contain any singularities, forward and inverse kinematics need to be calculated. The Denavit-Hartenberg notation was used for the kinematics, and can be seen in Fig. 2. Table IV shows the parameters associated with the Denavit-Hartenberg notation that have been used with Peter Corke's Robotic Toolbox to calculate both the forward and inverse kinematics [29]. The values of θ in Table IV relate to the angles that each joint needs to be capable of rotating in order to match the ROM of the human arm. These values can be seen in the previous section in Table III.

TABLE II: Anthropometric Data for the Arm [26]

	Females			**Males**
(cm)	*Min.*	*Max.*	*Mean*	*Mean*
Acromion-Radiale Length	24.90	37.10	31.12	33.52
Biacromial Breadth	28.30	42.20	36.53	41.57
Bicep Circumference	21.60	43.50	30.56	35.81
Forearm-CoG Length	25.80	39.20	31.77	34.90
Forearm Circumference	20.00	34.20	26.41	31.01
Forearm-Hand Length	34.20	52.70	43.99	48.02
Hand Breadth	6.70	9.20	7.82	8.83
Hand Circumference	15.20	21.40	18.66	21.23
Hand Length	14.50	22.00	18.11	19.33
Palm Length	8.80	13.00	10.87	11.65
Radiale-Stylion Length	16.90	29.70	24.13	26.79
Shoulder-Elbow Length	27.10	39.80	33.43	36.37
Shoulder Length	10.70	17.50	13.54	14.98
Wrist Circumference	12.40	18.30	15.48	17.59
Acromion-Axilla Length	5.80	14.50	9.61	11.17
Arm Length	56.70	86.60	72.20	78.65
Clavicle Link	14.20	21.10	18.29	20.81
Elbow Wrist Length	18.70	31.00	25.88	28.69
Functional Grip Reach	55.10	84.30	69.30	75.69
Vertical Grip Reach Down	47.80	73.30	60.69	66.32
Mass (kg)	**35.80**	**119.60**	**67.76**	**85.52**

TABLE III: Joint Ranges of the Human Arm [27][28]

Rotation	Shoulder	Elbow	Wrist
Flexion	180°	160°	90°
Extension	50°	145°	70°
Abduction	180°	-	25°
Adduction	50°	-	65°
Horizontal Abduction	135°	-	-
Horizontal Adduction	45°	-	-
Pronation	-	90°	-
Supination	-	90°	-

TABLE IV: Denavit-Hartenberg Parameters of BEAST

Joint i	$\theta_i(^\circ)$	$\alpha_i(^\circ)$	$r_i(mm)$	$d_i(mm)$
1	θ_0	0	120	0
2	θ_1	-90	101	0
3	90	90	101	0
4	θ_3	0	110	0
5	$\theta_4 + 90$	0	360	0
6	θ_5	0	320	0
7	θ_6	-90	70	0
8	θ_7	0	80	0

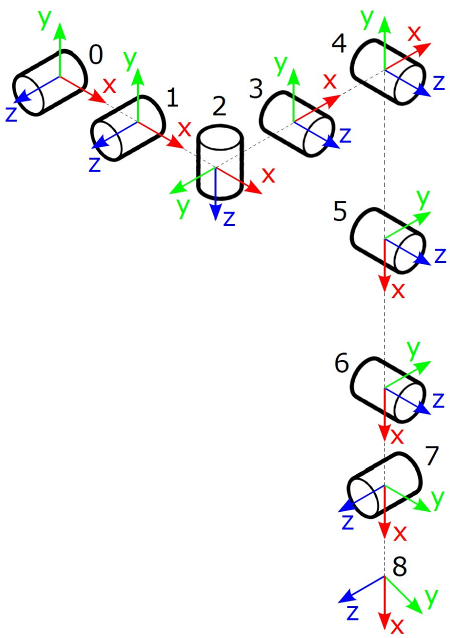

Fig. 2: Denavit-Hartenberg diagram showing the exoskeleton with the arm in the resting position

Using the Denavit-Hartenberg notation and parameters, the workspace of BEAST can be plotted; again using the Peter Corke Toolbox [29]. The various workspace plots of BEAST are shown in Fig. 3, with the workspace of just the wrist and the elbow, and in Fig. 4, with the workspace of the whole exoskeleton. These plots show that there are no gaps in the range of the exoskeleton, ensuring that rehabilitation can be carried out in full.

C. Actuation

BEAST is to be actuated through a cable system running from the motors on the back brace, to each of the joints. Two cables are needed for each of the joints, one for each direction. For the initial design, braided fishing line has been used due to it being thin but high in tensile strength; the particular braiding used for the prototype is capable of lifting 70lbs (32kg), with a diameter of 0.44mm. Fig. 5 shows a small prototype of the elbow joint and cable actuation that was used to test the feasibility of the cable system. As seen in the photo, this prototype uses 100:1 micrometals, which are likely to be replaced in the final prototype based on the torque requirements determined below. Size, weight and cost all need to be considered when choosing appropriate motors

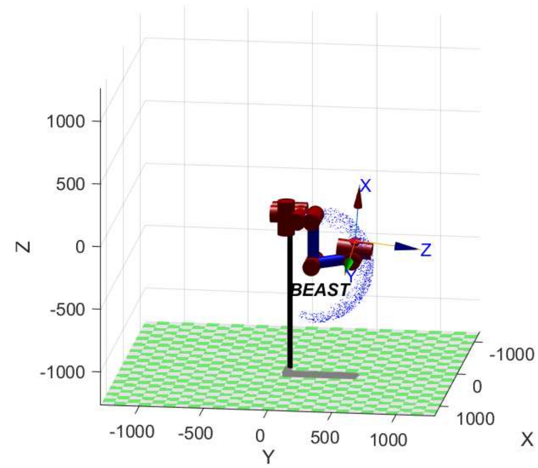

Fig. 3: Kinematic Workspace of BEAST Wrist and Elbow Joints

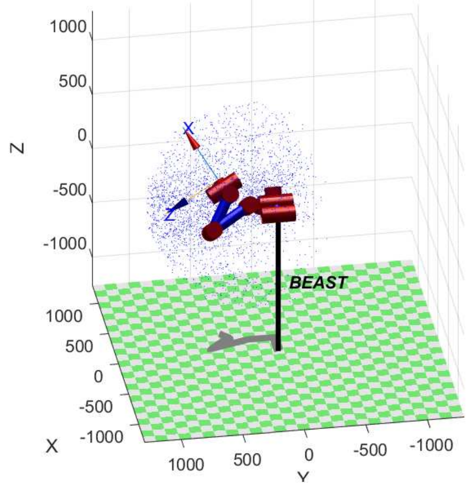

Fig. 4: Kinematic Workspace of BEAST

for this design due to the exoskeleton being wearable and with the intention of the exoskeleton being as low cost as possible. The torque required for each of the exoskeleton joints can be calculated using Equation 1. Information on torque requirements in exoskeletons could not be found in existing literature so is therefore fully explained below in the hopes it may help future new researchers.

$$Torque = Force \times Distance \tag{1}$$

In order to calculate the torque required for the wrist joint, the force and distance need to first be defined. The distance for the wrist joint is the distance from the centre of gravity (CoG) of the hand, to the wrist joint itself; and the force is the weight of the hand segment. Information on the mass and CoG of body segments was taken from [27]. It gives the weight of each body segment as a percentage of total body weight, and the CoG as a percentage of the length of the segment from the proximal end [27]. Table V outlines the necessary data for the torque calculations; the values used

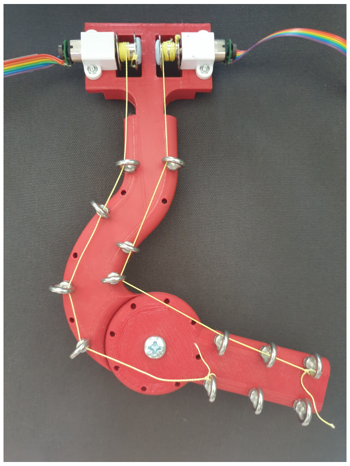

Fig. 5: Prototype of Elbow Joint and Cable Actuation Testing

TABLE V: Torque Calculation Values [26][27]

Segment	Mass (%)	Mass (kg)	Length (mm)	CoG (%)	CoG (m)
Hand	0.50	0.34	18.11	46.8	0.085
Forearm	1.57	1.06	43.99	43.4	0.191
Upper Arm	2.90	1.97	33.43	45.8	0.153

are focused on the average female with a mass of 67.76kg, following the data found in [26].

Using the data from Table V, the wrist torque can be calculated:

$$WristTorque = (0.34kg \times 9.81) \times 0.085m = 0.282Nm \quad (2)$$

When calculating the elbow torque, both the hand and forearm segments are taken into account. Firstly. the torque required to lift the forearm segment is calculated in the same way as before:

$$Torque = (1.06kg \times 9.81) \times 0.191m = 1.992Nm \quad (3)$$

This time when calculating the torque for the hand segment, the distance used must be the distance from the elbow joint, and is therefore the whole length of the forearm plus the distance from the wrist to the CoG of the hand segment, and so gives the torque required by the elbow joint to lift the hand segment:

$$Torque = (0.34kg \times 9.81) \times (0.4399m + 0.085m) = 1.744Nm \quad (4)$$

These two values of torque can then be added together to discover the final amount of torque needed to actuate the elbow joint:

$$ElbowTorque = 1.992Nm + 1.744Nm = 3.736Nm \quad (5)$$

This same method is also used to calculate the torque required to actuate the shoulder joint. First by calculating the torque required by the shoulder to actuate each joint individually and then adding them together. The torque required to actuate the upper limb segment is calculated first:

$$Torque = (1.97kg \times 9.81) \times 0.153m = 2.951Nm \quad (6)$$

Followed by the torque required by the shoulder to actuate the forearm segment:

$$Torque = (1.06kg \times 9.81) \times (0.3343m + 0.191m) = 5.481Nm \quad (7)$$

And lastly, the torque required by the shoulder to actuate the hand segment:

$$Torque = (0.34kg \times 9.81) \times (0.3343m + 0.4399m + 0.085m) = 2.855Nm \quad (8)$$

These three values of torque can then be added together to give the total torque required for the shoulder joint to actuate the arm:

$$ShoulderTorque = 2.951Nm + 5.481Nm + 2.855Nm = 11.288Nm \quad (9)$$

These values of torque can then be used to determine the amount of power needed for each set of motors that will actuate the cables. A safety factor is also needed to ensure that the motors are actually providing more than enough torque so that the exoskeleton does not have any issues when being used.

IV. PATIENT NEEDS

Many existing exoskeletons in literature have a design phase, followed by a testing phase and eventually a clinical trial. The testing phase picks up on the engineering issues and limitations that the design might have, but it is often not until the clinical trial phase that feedback is gained from patients and medical professionals. The aim with this design is to include these essential users at the optimisation phase, so that the final design is more inline with what users want and can use in the rehabilitation setting. In order to gather feedback, two online surveys are to be distributed; one for patients that have suffered from a stroke; and one for medical professionals that carry out rehabilitation of the upper limb in any capacity. Once the survey has been completed, the data will be gathered and analysed in order to create an optimisation strategy for the design of BEAST. The questions have been designed with the aim of using Quality Function Deployment (QFD) to analyse the data and create a list of customer requirements that can then be related to the engineering specification. A future paper is planned that will present the results and QFD analysis of the patient and therapist surveys.

V. CONCLUSIONS

In order for stroke rehabilitation to confront the ever growing numbers of patients suffering from the effects of stroke, it needs to embrace everything that modern technology can offer. Exoskeletons are capable of creating a more consistent standard of rehabilitation, while still allowing the customisation that patients require. By using cable actuation in a 7-DOF exoskeleton for the wrist, elbow, and shoulder; BEAST allows patients to be fully independent when carrying out their rehabilitation. While many of the existing bilateral exoskeletons aim to solve one or two of the issues surrounding rehabilitation, BEAST aims to solve many more of them; from reducing the time and money that may be spent on travelling to and from the hospital; to reducing the time between the onset of stroke and the start of rehabilitation; to creating an independent and personalised experience. BEAST brings a new wearable device to the table that hopes to provide a more effective and successful method of rehabilitation to the home environment by ensuring all patients receive the fastest and most appropriate care for their individual needs.

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