A review of assistive devices for arm balancing

A.G. Dunning
Dept. Biomechanical Engineering
Delft University of Technology
Delft, The Netherlands
a.g.dunning@tudelft.nl

J.L. Herder
Dept. Precision and Microsystems Engineering
Delft University of Technology
Delft, The Netherlands
j.l.herder@tudelft.nl

***Abstract*—Due to neuromuscular disorders (e.g., Duchenne Muscular Dystrophy) people often loose muscle strength and become wheelchair bound. It is important to use muscles as much as possible. To allow this, and to increase independency of patients, an arm orthosis can be used to perform activities of daily life. The orthosis compensates for the gravity force of the arm, allowing people to perform movements with smaller muscle forces. For patients, the aesthetics of the orthosis is one of the critical issues. This paper presents the state-of-the-art in passive and wearable active arm orthoses, and investigates how to proceed towards a suitable structure for a wearable passive arm orthosis, that is able to balance the arm within its natural range of motion and is inconspicuous; in the ideal case it fits underneath the clothes. Existing devices were investigated with respect to the body interface, the volume, and the workspace. According to these evaluation metrics it is investigated to what extent the devices are wearable and inconspicuous. Furthermore, the balancing principle of the devices, the architecture, force transmission through the devices, and alignment with the body joints are investigated. It appears that there is only one wearable passive orthosis presented in literature. This orthosis can perform throughout the natural workspace of the arm, but is still too bulky to be inconspicuous. The other passive orthoses were conspicuous and mounted to the wheelchair. Except one, the wearable active orthoses were all conspicuous and heavy due to a large backpack to enclose the actuators. They also could not achieve the entire natural workspace of the human arm. A future design of an inconspicuous, wearable, passive arm orthoses should stay close to the body, be comfortable to wear, and supports pronation and supination.**

Keywords—arm support; orthosis; upper extremity; wearable; inconspicuous; assistive; balancing

I. INTRODUCTION

People with neuromuscular disorders often rely on assistive devices to perform Activities of Daily Living (ADL). Neuromuscular disorders (e.g., muscular dystrophy, spinal cord injuries or stroke) affect the muscles of the patient. The muscles deteriorate, contractures are formed due to the disuse of the arm, and eventually results in losing arm function.

One of the most common muscular dystrophies is Duchenne Muscular Dystrophy (DMD). DMD is caused by a mutation on the X-chromosome and has a prevalence of 1 for every 3500 male births [1]. DMD is characterized by progressive degeneration of the muscles. It starts with the most proximal muscles (e.g., upper legs, upper arms, shoulders), and proceeds to the more distal muscles of the human body (e.g., wrist, fingers). The disease affects the upper legs of the patient before they are 10 years old, and they will become confined to a wheelchair. When the upper arm muscles deteriorate, boys with DMD experience significant lack of muscle strength and can no longer perform ADL. Consequently, they become highly dependent on their caregivers. In addition, most people with DMD will develop severe psychological problems, due to restricted participation in society [2, 3].

To compensate for the muscle weakness and the impossibility of executing ADL, and to be able to participate in society, boys with DMD often depend on assistive devices. For example, a wheelchair is used to compensate for the loss of leg function. For the arm function, an arm support can be used to augment the muscle strength, to lift their arm again, and consequently become more independent. These supporting devices are also called orthotic devices, or in short orthoses. Orthotic devices should fulfil many requirements to encourage use in daily life and improve the quality of life. These requirements include aspects of comfort, easy donning and doffing, force transmission to the body, adjustable to the body, functionality, etc. Another important requirement is the aesthetics. One of the key assumptions for the project “Flextension”, and also stated in [4], is that the users prefer an inconspicuous device that gives a natural support.

Much research on arm orthoses has been conducted in recent years. These devices can be categorized into three groups [5]: 1) robotic manipulators, 2) powered (active) orthoses and 3) non-powered (passive) orthoses. In the first group, several devices are developed and commercialized, including Jaco [6] and iARM [7]. These devices are intended for patients without any arm function. All these devices are heavy and very conspicuous, mounted to the wheelchair and act like an extra arm instead of supporting the arm of the user. While a larger device is acceptable for training activities, a wearable device is preferred for assistance in ADL [8].

A quick scan of previous research that presented the state-of-the-art for active [9] and passive assistive devices [10] showed that wearable passive orthosis are rare. In addition, only a few active orthoses are wearable, but these remain conspicuous.

To investigate the assumption that a critical design requirement of an arm orthosis is inconspicuous, this study proceeds towards a suitable structure for a wearable passive

This research is part of the project "Flextension", sponsored by Technology Foundation STW, project 11832.

arm orthosis that is able to balance the arm within its natural range of motion and is inconspicuous; in the ideal case it fits underneath clothes. To achieve this goal, this study presents and discusses a review of the state-of-the-art in passive and wearable active upper limb assistive devices, to investigate the inconspicuousness and wearability of the devices. Therefore, it is proposed to look into three evaluation metrics: 1) the interface points with the body, 2) the volume, and 3) the workspace of the devices. Additionally, this paper investigates the possibilities of combining the critical features of both passive and active orthoses into a wearable, inconspicuous passive orthosis to improve the design of future arm supports.

II. METHOD

A. Search Method

This study is separated into two parts. First, the state-of-the-art of passive arm orthoses is investigated. For this part, both wearable and non-wearable passive orthoses were considered. In this study, a passive orthoses is defined as a device that can balance the arm fully passive for a certain range of motion. The balancing principle is decisive, meaning that even if the balancing force can be adjusted actively, it is still considered as a passive orthoses.

Second, the active orthoses are investigated. After a quick scan of all the available active orthoses it was decided to choose for the wearable arm orthoses only. In this study, an active orthoses is defined as a device that does not balance the arm, but dictates the movements of the arm using actuators. In this study, the arm is considered to be from the shoulder to the forearm, neglecting the wrist and the fingers.

After analyzing the topic and considering the constraints of this study, a search strategy was defined. Key subjects were determined and for each key subject a set of related keywords, including synonyms and related terms, were defined. The sets of keywords were used as search terms in the search engines Scopus [11] and Espacenet [12]. With Scopus, journal articles and conference proceedings were searched, while Espacenet was used to search for patents. In total six sets of keywords were used to define the key subjects: 1) arm support, 2) wearable, 3) structure, 4) static balancing, 5) adjusting force, and 6) actuation/control. An overview of the sets of keywords is shown in Table 1. To optimize and narrow the search results, different combinations of keywords were made. Cross-referencing is also an important step to find relevant articles. After an extensive search, the articles were assessed by reading the title and the figures, and if the article seemed relevant, the abstract was read.

B. Classification and comparison

It is important to define some constraints to formulate the design problem. To recapitulate, the goal is to proceed towards a suitable structure for a wearable, inconspicuous passive orthosis that can balance the arm within the natural workspace and fits underneath clothing. For this study, it is stated that the orthosis must fit within 20 mm from the body, to be inconspicuous and fits underneath clothing. Three evaluation metrics were proposed to investigate the inconspicuousness and wearability of existing devices.

TABLE I. OVERVIEW OF THE SETS OF KEYWORDS USED IN SCOPUS AND ESPACENET.

Sets	Keywords
1. Arm support	- Robot arm - Orthosis, exoskeleton, assistive device, arm support - Arm weakness, muscle weakness
2. Wearable	- Wearable, portable, mobile - Body-fitting, suit, harness
3. Structure	- Human arm, bionic, upper extremity, upper limb
4. Static balancing	- Static balancing, neutral equilibrium, zero stiffness, gravity compensation
5. Adjusting force	- Manipulator - Adjustable, variable force - Control force
6. Actuation/ control	- Therapy assistant - Rehabilitation - Actuator, control

The first evaluation metric is the body interface. For each orthosis found in literature, it is determined which body part the device is attached to and to what extend the device is wearable.

The second evaluation metric quantifies the devices' volume to give insight on how inconspicuous the devices are. For each orthosis, the volume within 20 mm from the skin around the whole arm, including the trunk, was calculated and compared with the available volume around the arm and trunk. Excess volume that does not fit within 20 mm from the skin was also calculated. The volume of each device was calculated in the position that the arm is lying on the arm rest (90 degrees flexion of the elbow). Note that all values that could not be identified in literature were estimated from figures and movies, based on anthropometric values [13].

Finally, the workspace is the third evaluation metric. The workspace is defined as the volume of space where the end-effector of the orthosis can reach, measured along the horizontal x and y-axis, and the vertical z-axis (Fig. 3). This workspace was estimated or calculated and compared with the workspace of the center of gravity of the whole arm of a healthy child between 12-14 years, extracted from the DINED anthropometry database [13].

Furthermore, this study investigated the structure of the orthosis, the architecture (serial or parallel), the balancing principle for passive devices, the force transmission through the device, and the alignment with the body joints. It also investigated which degrees of freedom (DoF) are supported by the device. This could be 3 DoF in the shoulder (abduction/ adduction, flexion/extension, and rotation), and 2 DoF in the elbow (flexion/extension, and pronation/supination).

III. RESULTS

In total, twelve passive arm orthoses and eleven wearable active devices were found in literature that are considered relevant. These devices were designed for assisting daily life, but also for rehabilitation purposes. Below, a short description of the general findings of passive and active orthoses is given. After that, the results for the three evaluation metrics are shown.

Only one passive device is wearable [10]. The others are mounted to the wheelchair [14-24]. Two points on the wheelchair are used to attach the orthoses. One is behind the backseat of the wheelchair [14,17,19,20,22,23] and the other is at the side [15,16,18,24], where it replaces the armrest of the wheelchair.

All passive orthoses have a serial architecture, meaning that the base (i.e., wheelchair or trunk) is connected only to the forearm by a single chain of links. Most of them allow all of the defined degrees of freedom of the arm, except support of pronation and supination. This is only possible by movements of the bone with respect to the skin inside the support cup.

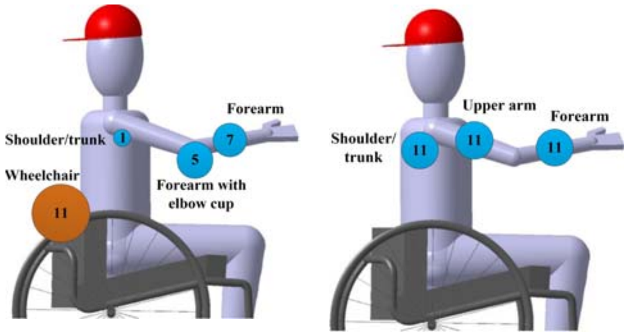
The arm is balanced with spring mechanisms. The spring mechanisms are constructed in combination with the arm to form an energy free system [25]. Several springs are used in the different mechanisms, varying from conventional helical springs [14,16,19,21], constant torque springs [22], to rubber bands [10,18,20].

Some other noticeable features for passive orthoses were found in literature. Some devices only lift 75% of the weight of the arm, while 25% of the arm weight is supported by the shoulder [16,23]. In some devices the upper arm and forearm were balanced independently [10,17], offering an optimized balancing quality for different positions of the arm. It is also seen that some devices use a minimal construction at the elbow and forearm, to prevent interference with the table or other objects where the arm can rest [17].

The passive orthosis with the largest volume within, and the smallest volume violating the prescribed available volume is the Wilmington Robotic Exoskeleton (WREX) [10]. Also, it is the only device that can be worn with a back brace. The structure is attached to the trunk and follows the arm closely along the shoulder to the forearm. With rubber bands the upper arm and forearm can be balanced independently.

Wearable active devices have the same kinematic architecture. They all run parallel to the arm from the trunk, via the shoulder to the forearm. Some devices use a mechanism to prevent misalignments with the body joints. For example, the use of a 3RRR spherical parallel shoulder mechanism [26], or a special 3-link shoulder mechanism allowing scapula motion [27]. In [28], a compliant soft-orthotic device is used to prevent misalignments.

In active orthoses, the actuators are placed locally at the joints [27,34], or stored in backpacks of large volume [29-32]. The forces from the actuators are transmitted to the joints with cables [28,30,32-34]. Since cables can only transfer tension forces, a combination of cables around the arm is used. In some devices pneumatic artificial muscles are used as actuators [29,32,34]. These are compliant and light-weight actuators, which can act and be placed in the same way as human muscles. The forces from the body are transferred to the structure through rigid links in the orthosis.



(a) *(b)*

Figure 1. Representation of the interface points on the body or wheelchair for (a) passive orthoses and (b) active orthoses.

In Fig. 1, a representation of the interface points of the orthoses with the body or wheelchair is shown. In Fig. 1a, it is shown that all orthoses, except one, are mounted to the wheelchair. These devices are not wearable. They are all connected with the body at the forearm. Some devices have an extra cup to the elbow to prevent the arm from falling out of the support cup during particular movements [15,17-20,22]. In Fig. 1b, the interface points of the wearable active orthosis are shown. All devices are parallel to the arm, connected to the trunk, upper arm and forearm. In contrast to the only wearable passive device, which has a serial structure along the arm.

Fig. 2 shows the calculated volumes of the devices. The available volume within 20 mm from the body is approximately 0.01 m^3. All passive orthoses use a small amount of volume within 20 mm from the body, but violate the prescribed available volume with a large amount of volume. The WREX scores the best on this metric. It exploits a lot of volume close to the body, and only a small amount is violating this available volume. Most active devices use a large amount of volume close to the body. However, compared to the passive orthoses, some devices violate the available volume with a relatively large amount of volume. This is mainly due to local actuators or a large structure on the back, where all the actuators are situated. Only in [28] a device is shown that stays close to the body. It should be mentioned that this device only supports shoulder abduction/adduction. If more DoF would be supported, the device needs more cables, which would increase the overall size.

In Fig. 3, the workspace of the orthoses can be seen. Data was not available for every orthosis. The horizontal lines (blue, green, and red) represent the maximum and minimum boundaries of each axis (*x*, *y*, *z*, respectively). For five passive orthoses [14,19,21,23,24] the workspace is much larger than needed for the human arm. The WREX approaches the natural workspace of the arm very well. Other devices have difficulties to perform the upward movement for the natural range of motion of the human arm. The wearable active orthoses all have a smaller workspace than the human arm. Only the ABLE [30] reaches the complete workspace along the *x* and *y*-axis.

IV. Discussion

The results in Fig. 1 show that only one passive orthoses is wearable. The others are connected to the wheelchair and also not close to the body. Some designs focused on the aesthetics, but in general they are not wearable underneath clothing, which makes them very conspicuous. All the passive orthoses use a serial linkage from the base (i.e., wheelchair or trunk) to the forearm. With such architecture, there are some positions of the arm where the device searches for the best position, which could mean that some links are positioned far from the body. This has to be kept in mind when designing a serial linkage that has to stay close to the body. The WREX has the best solution for this because it is designed to follow the arm contours. It moves parallel and as close to the arm as possible. In contrast to passive orthoses, all wearable active orthoses are connected to the trunk, upper arm and forearm. The devices stay closer to the body during movements, because they move parallel to the arm. But very good alignment with the body joints is needed to prevent singularities and injuries. This was already discussed by Schiele et al. [37], who stated that an ergonomic exoskeleton must not copy the human's kinematic

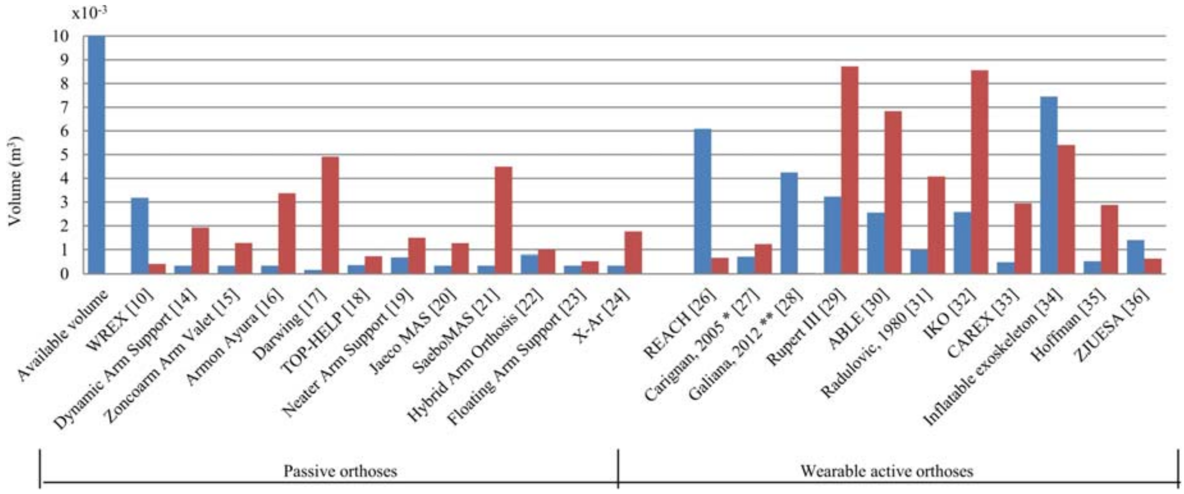


Fig. 2. Volume of the devices within 20 mm from the body (blue) and violating 20 mm from the body (red). If the data was not available in the articles, the values were estimated based on figures and movies. *A torso structure was not mentioned in the article, so the volume is not taken into account. ** Only shoulder abduction/adduction is supported by this device.

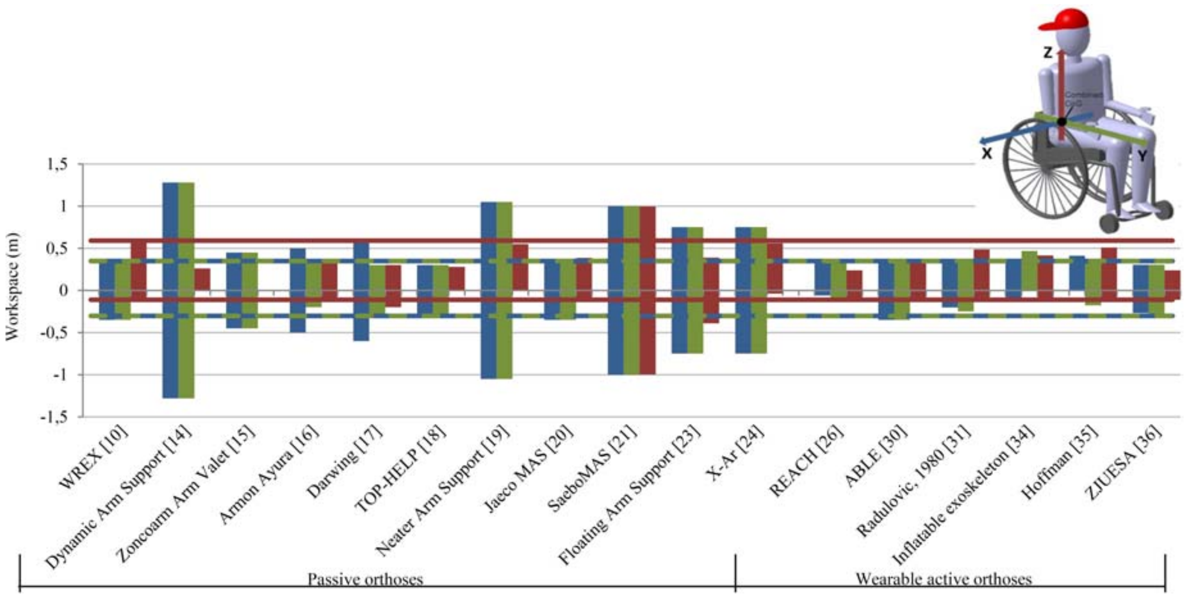


Fig. 3. Workspace of the end-effector of the orthoses in x-direction (blue), y-direction (green) and z-direction (red). The horizontal lines (blue, green, and red) represent the maximum and minimum boundaries of each axis (x, y, z, respectively). If the data was not available in the articles, the values were estimated based on figures and movies.

structure to be robust to misalignments. The opinion of the authors is that the best way towards a wearable passive arm orthosis with a natural workspace, is the design of a serial linkage connected to the trunk and the forearm that stays very close to the body.

Fig. 2 shows the volumes of the orthoses. Almost all passive devices utilize a small amount of volume within the 20 mm from the body. The serial linkages from the wheelchair to the forearm of the user were not designed in a way that will be close to the body. Not all devices were designed to be close to the body, but for the final goal of the project, exceeding the available volume represents a solution that is inconspicuous, heavy and not wearable. Only the WREX shows good results. Recall that the volumes were calculated for one position of the arm (lying on the arm rest). The volumes within and violating the available volume could change with different arm motions.

Comparing the passive with the wearable active devices, the active devices have relatively larger amounts of volume violating the proposed available volume. This is mainly due to the actuators that are placed in a large backpack. Although the parts connected to the arm approach the required volume, the backpack is conspicuous. This also adds weight on the back of the user that affects to wearability and user comfort. Moreover, since DMD patients are wheelchair bound, it is not possible to place such a large amount of volume on the back. Most of the devices with this structure use cables to transfer the forces from the actuators to the joints. Cable transmission implies high force capacity, high stiffness, and low inertia. However, there is also friction involved. This has to be minimized to apply such a structure for patients with very low muscle strength. With cable actuation, shear forces can be exerted on the user. The devices with local actuators at the limbs add weight along the extremities. This makes the limbs heavy, conspicuous and no natural movements are ensured.

Some interesting passive elbow orthoses were found in literature [38,39]. These results were not taken into account because they did not support the whole arm. These devices were very close to the body and fit within the volume enclosed by 20 mm from the body, they could only perform flexion and extension of the elbow.

In Fig. 3, it can be seen that the serial linkages of the passive orthoses can reach the workspace of the human arm along the horizontal *x* and *y*-axes. The full range of motion along the vertical *z*-axis is not supported in all devices. This can be justified because reaching above the shoulder is not required to complete many critical activities of daily life. Therefore, a design strategy could be to neglect the full vertical range of motion in future designs, focusing only on support of the most critical activities of daily life. There are three devices with a very large workspace [14,19,21]. The reason is unclear, because now all the material needed to reach the boundaries of the workspace has to go somewhere when the arm is close to the body. On the other hand, the active orthoses have smaller workspaces than the natural workspace of the human arm. The active devices are connected to the body at three points. That requires movements along the arm, but it also requires very good alignments with the body joints to prevent misalignment. These alignment difficulties affect the workspace of the orthoses and the human arm and the comfort of wearing the orthosis [37]. For future designs, a serial linkage that follows the arm contours with special joints at the shoulder and elbow that prevent misalignment with the body joints is proposed.

The passive orthoses use springs mechanisms to balance the arm in the combined centre of gravity of the upper and forearm. In this way, only one interface point with the arm is required. Besides the gravity compensation, the use of springs also introduces some small damping behaviour. This can have a positive effect on precision tasks, like writing and eating with a spoon. However, a perfect balancing quality has an instable behaviour. There should be a trade-off between the perfect or near perfect balancing quality, where the user must have minimal muscle strength to overcome the remaining gravity force to move the structure.

There are two other remarks that can be made based on the results. First, only three orthoses supports pronation and supination. This movement is important for many critical activities of daily life, for example eating and drinking. For future designs, it is proposed to include support for pronation and supination to achieve a more natural range of motion of the arm. Second, in two devices the upper arm and forearm were balanced independently. This could be very advantageous, because the balancing force of the arm differs through the entire workspace.

Finally, it should be mentioned again that this research focused only on the inconspicuousness and wearability of existing assistive devices. For future designs, other aspects (e.g., functionality, comfort, easy donning and doffing, etc.) should be taken into account. These aspects are of great importance to encourage the use of an arm orthosis in daily life and improve the quality of life.

V. CONCLUSIONS

An overview of the state-of-the-art of passive and wearable active arm orthoses has been presented. The wearability and inconspicuousness of the devices is investigated with respect to three evaluation metrics: 1) the body interface, 2) the volume, and 3) the workspace of the devices.

It is found that there are only 4 out of 23 devices that are wearable and have a relatively small amount of volume violating the available volume, which is enclosed by 20 mm from the arm and trunk. There is only one wearable passive orthosis presented in literature that can perform within the entire natural workspace of the human arm. The others are mounted to the wheelchair, rather bulky, and not inconspicuous. The passive devices have a serial structure from the forearm to the wheelchair or trunk. Wearable active devices are all attached to the trunk, upper arm and forearm. They have large structures to enclose the actuators. This is commonly positioned at the back of the user. These backpacks are conspicuous, add weight to the user, and are not suitable to use when sitting in a wheelchair. Some passive devices support a larger workspace than the natural workspace of the human arm. Active devices have a smaller workspace than the human arm, because the parallel structures with three body interface points need alignment with the body joints to prevent misalignment. This affects the workspace of both the orthoses and the arm.

For future designs of a wearable, inconspicuous arm orthosis, a serial linkage from the trunk to the forearm is proposed. This orthosis should be aligned and remain close to the body, without interfering with the body and causing user discomfort. The orthosis should include a support for pronation and supination of the forearm. Independent balancing of the upper arm and forearm is advantageous. If the orthosis needs actuation, remote actuators decrease the inertia of the moving limbs and can be placed out of sight.

REFERENCES

[1] A.E.H. Emery, "Population frequencies of inherited neuromuscular diseases - a world survey," Neuromuscul. Disord, vol. 1(1), pp. 19-29, 1991.

[2] J. Rahbek, B. Werge, A. Madsen, J. Marquardt, F.B. Steffensen, and J. Jeppesen, "Adult life with Duchenne muscular dystrophy: observations among an emerging and unforeseen patient population," Dev. Neurorehabil., vol. 8(1), pp. 17-28, 2005.

[3] M.A. Grootenhuis, J. de Boone, and A.J. van der Kooi, "Living with muscular dystrophy: health related quality of life consequences for children and adults," Health Qual. Life Out., vol. 5:31, 2007.

[4] T. Rahman, W. Sample, R. Seliktar, M. Alexander, and M. Scavina, "A body-powered functional upper limb orthosis," JRRD, vol. 37(6), pp. 675-680, 2000.

[5] L.F. Cardoso, S. Tomazio, and J.L. Herder, "Conceptual design of a passive arm orthosis," Proc. ASME DETC, Montreal, Canada, Sep. 29-Oct. 2, 2002.

[6] Focal Meditech JACO, http://www.focalmeditech.nl

[7] Exact Dynamics iARM, http://www.exactdynamics.nl

[8] E.A. Brackbill, Y. Mao, S.K. Agrawal, M. Annapragada, and V.N. Dubey, "Dynamics and control of a 4-dof wearable cable-driven upper arm exoskeleton," Proc. IEEE ICRA, Kobe, Japan, May 12-17, 2009.

[9] R.A.R.C. Gopura, and K. Kiguchi, "A brief review on upper extremity robotic exoskeleton systems," Proc. IEEE ICIIS, Kandy, Sri Lanka, Aug. 16-19, 2011.

[10] T. Rahman, W. Sample, S. Jayakumar, M.M. King, J.Y. Wee, R. Seliktar, M. Alexander, M. Scavina, and A. Clark, "Passive exoskeletons for assisting limb movement," JRRD, vol. 43(5), pp. 583-590, 2006.

[11] Scopus: http://www.scopus.com

[12] Espacenet: http://www.espacenet.com

[13] DINED: http://dined.io.tudelft.nl

[14] G. Kramer, G.R.B.E. Römer, and H.J.A. Stuyt, "Design of a dynamic arm support (DAS) for gravity compensation," Proc. IEEE ICORR, Noordwijk, The Netherlands, Jun. 12-15, 2007.

[15] ZoncoArm Arm Valet, http://www.zoncoarm.com

[16] J.L. Herder, "Development of a statically balanced arm support: ARMON," Proc. IEEE ICORR, Chicago, IL, USA, Jun. 28–Jul. 1, 2005.

[17] Focal Meditech Darwing, http://www.darwing.nl/

[18] Focal Meditech TOP/HELP, http://www.focalmeditech.nl

[19] Neater Solutions Arm Support, http://www.neater.co.uk

[20] Jaeco Orthopedic Elevating MAS, http://www.jaecoorthopedic.com

[21] Saebo MAS, http://www.saebo.com

[22] N. Benjuya and S.B. Kenney, "Hybrid arm support," JPO, vol 2(2), pp. 155-163, 1990.

[23] J. Skorecki, "A "floating arm" support for wheel-chairs," Ann. Phys. Med, vol. 9(2), pp. 67-68, 1967.

[24] Equipois X-Ar, http://www.equipoisinc.com

[25] J.L. Herder, "Energy-free systems: theory, conception and design of statically balanced spring mechanisms," PhD-thesis, Delft University of Technology, Delft, The Netherlands, November 2001.

[26] P. Bosscher, and E. LaFay, "Haptic cobot exoskeleton: concepts and mechanism design," Proc. ASME IDETC, Philadelphia, PA, USA, Sep. 10-13, 2006.

[27] C. Carignan, M. Liszka, and S. Roderick, "Design of an arm exoskeleton with scapula motion for shoulder rehabilitation," Proc. IEEE ICAR, pp. 524-531, Washington DC, USA, Jul. 18-20, 2005.

[28] I. Galiana, F.L. Hammond III, R.D. Howe, M.B. Popovic, "Wearable soft robotic device for post-stroke shoulder rehabilitation: identifying misalignments," Proc. IEEE/RSJ IROS, Vilamoura, Algarve, Portugal, Oct. 7-12, 2012.

[29] T.G. Sugar, J. He, E.J. Koeneman, J.B. Koeneman, R. Herman, H. Hang, R.S. Schultz, D.E. Herring, J. Wanberg, S. Balasubramanian, P. Swenson, and J.A. Ward, "Design and control of RUPERT: a device for robotic upper extremity repetitive therapy," IEEE Trans. Neural Syst. Rehabil. Eng., vol. 15(3), pp. 336-346, 2007.

[30] P. Garrec, J.P. Friconneau, Y. Méasson, and Y. Perrot, "ABLE, an innovative transparent exoskeleton for the upper-limb," Proc. IEEE/RSJ IROS, Nice, France, Sep. 22-26, 2008.

[31] R. Radulovic, J.B. Piera, B. Cassagna, A. Grossiord, and G. Boruchowitsch," Prosthet. Orthot. Int., vol. 4, pp. 101-105, 1980.

[32] F. Martinez, I. Retolaza, A. Pujana-Arrese, A. Cenitagoya, J. Basurko, and J. Landaluze, "Design of a fice actuated DoF upper limb exoskeleton oriented to workplace help," Proc. IEEE/RAS-EMBS BioRob, Scottsdale, AZ, USA, Oct. 19-22, 2008.

[33] S.K. Agrawal, V.N. Dubey, J.J. Gangloff jr., E. Brackbill, Y. Mao, and V. Sangwan, "Design and optimization of a acble driven arm exoskeleton," J. Med. Devices, vol. 3(3), p. 031004, 2009.

[34] H. Kobayashi, A. Uchimura, Y. Isihida, T. Shiiba, K, Hiramatsu, M. Konami, T. Matsushita, and Y. Sato, "Development of a muscle suit for the upper body – realization of abduction motion," Advanced Robotics, vol. 18(5), pp. 497-513, 2004.

[35] A.H. Hoffman, H.K. Ault, H. Toriumi, S.A. Smith, and C. Felice, "The design and kinematic evaluation of a passive wearable upper extremity orthosis," Proc. RESNA 25th Int. Conf., vol. 22(1), pp. 160-162, 2002.

[36] J. Zhang, H. Fu, Y. Dong, Y. Zhang, C. Yang, Y. Chen, "Novel 6-DoF wearable exoskeleton arm with pneumatic force-feedback for bilateral teleoperation," Chinese Journal of Mechanical Engineering, vol. 22(3), 2012.

[37] A. Schiele, "Fundamental of ergonomic exoskeleton robots," PhD-thesis, Delft University of Technology, Delft, The Netherlands, May 2008.

[38] D.H. Plettenburg, "The WILMER Elbow orthosis," Proc. IEEE ICORR, Noordwijk, The Netherlands, Jun. 12-15, 2007.

[39] M.M. Wierzbicka and A.W. Wiegner, "Orthosis for improvement of arm function in C5/C6 tetraplegia," JPO, vol 8(3), pp. 86-92, 1996.