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Development of a Mobile Arm Support (Armon): Design Evolution and Preliminary User Experience

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Abstract—**This paper regards three design iterations of a mobile arm support (Armon): the initial proof-of-concept version, the intermediate clinical-experimental version, and the present first-product version. This is done by comparing the mechanical architecture, features and specification on the one hand, and some user experiences with these successive devices on the other hand. Furthermore, several users report on their use of the device in activities of daily living.**

I. Introduction

PEOPLE suffering from neuromuscular diseases have trouble lifting their arms against gravity, which greatly challenges many elementary activities of daily living (ADLs). Fortunately, many of these people maintain sensitivity and residual strength in their hands. Spinal Muscular Atrophy (SMA) is a disease to which this applies. SMA has an incidence in the range of 4 per 100,000 [1]. This condition affects the proximal joints (shoulders, hips) first and is perceived as being progressive.

For these people, a device is desired that enables them to make use of their hands in a larger range of motion than they can reach by themselves. Known assistive devices available can be subdivided in three main groups [2] that are mentioned here with some illustrative examples. A first group contains rehabilitation robotic manipulators. Several of these have been developed and were successfully commercialized [3], including the MANUS, the Handy, and the Raptor. A second group consists of powered orthoses, for example the exoskeletons MULOS [4] and the Golden Arm [5], and the active overhead suspension presented in [6]. A third group is formed by non-powered orthoses, typically based on gravity balancing mechanisms using springs. Chyatte and Skorecki are two of the earliest [7-8], while current efforts are undertaken by Rahman [9]. The Jaeco MAS [10] and the TOP-HELP [11] are two examples of commercially available non-powered orthoses.

For the weakest patients, who in some cases have virtually no muscle force, robotic manipulators and powered orthoses are most suitable. However, if the user can be classified according to Brooke [12] in category 3-5, a passive arm orthosis is usually preferred [13]. Passive (non-powered) orthoses require some muscle force for accelerating and decelerating, and to overcome friction and balancing errors. Moreover, load changes, that occur for instance when picking up objects or change of clothing need to be overcome by muscle force. This effort can be substantial, and disqualifies non-powered orthoses for many patients.

The support force in most currently available passive arm supports cannot be adjusted by the user. In addition, some suffer from limited range of motion (e.g. only horizontal), non-perfect balancing quality (e.g. due to rubber springs), or problems related to comfort (donning and doffing, sliding and perspiration in trough). Therefore, it was concluded that there is a need for one that acts with satisfying functionality, comfort, safety and aesthetics.

This paper reviews the design process of one particular a passive arm support, i.e. the Armon, and reports on its use in the daily life of several users. Although by no means a formal evaluation study, the paper aims to relate the technical performance of the device to its applicability in everyday life, and to reflect on possible improvements.

The paper is structured as follows: First, the technical development of the Armon is reviewed. Subsequently the paper reports on its use in activities of daily living through case studies of several users. Finally, possible improvements will be discussed.

II. Technical development

The development of the Armon was triggered by the desire to reduce the operating effort associated with non-powered orthoses, so as to allow a greater population access to a passive device. In robotic manipulators, all degrees of freedom of the robotic arm, wrist and gripper need to be controlled; in powered orthoses only the robotic arm; but in non-powered orthosis no control is needed as the device follows the natural arm movement, at the cost of some operating power requirement for acceleration, deceleration, and overcoming friction and balancing error. Therefore, great emphasis was placed on striving for low friction and zero balancing error, while at the same time high functionality (range of motion) and aesthetics were aimed at.

The study was primarily directed at people suffering from SMA, although the result has a much wider application potential, including persons suffering from other neuromuscular diseases (e.g. MS, Becker, Shoulder Girdle), people with certain paralyses, and persons performing computer work or general desk tasks suffering from or at risk of RSI (repetitive strain injury) or similar conditions.

The next three subsections will describe the technical

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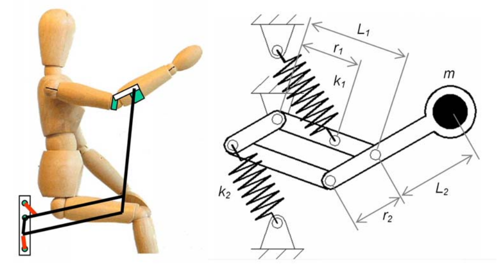
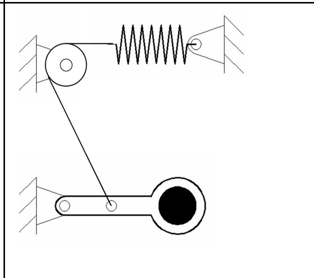
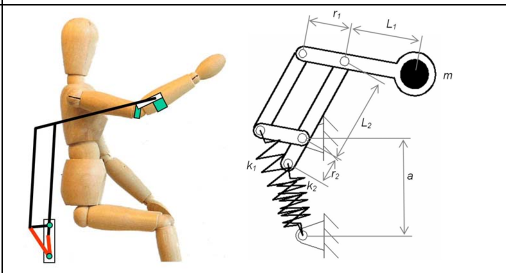
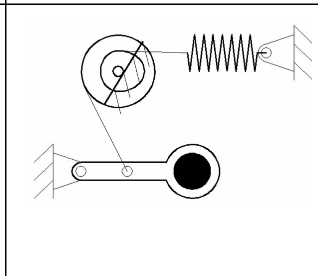
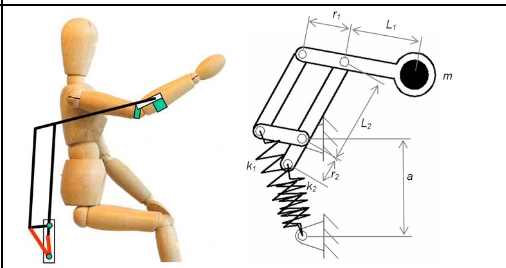
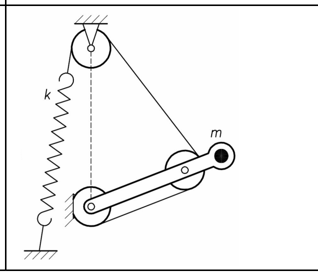
	Kinematic architecture	Balancing principle	Picture	Error
Mark I				5% (*)
Mark II				3% (#)
Mark III				0,5% (*)

Figure 1 Overview of technical development of the Armon showing kinematic architecture, balancing principle, and performance: (*) maximum required operating force consisting of balancing error and friction as measured in an experiment; (#) mean balancing error as determined in simulation.

development of three generations of prototypes of the device.

A. Mark I: Proof of Concept

One obvious solution for eliminating gravity is to support the full arm weight by a device. A biomechanical force analysis revealed that this is not the only solution [2]. A paradigm shift can be made by realizing that the patient's shoulder joint is very well capable of carrying half of the upper arm mass. The other half is transferred to the forearm and composed with the forearm mass to a combined center of mass. Thus, the patient's arm is perfectly statically balanced, even though only around 75% of the patient's arm mass is actually supported by the orthosis, while only one interface position is required. Furthermore, basically any spring loaded gravity equilibrator can be used as a basis for the mechanism and it does not need to be arranged alongside the arm. This concept seemed very promising and a project was started to develop an orthosis based on this principle.

A known gravity balancer architecture was found to qualify for this task ([14], [15], [16]). Kinematically, the mechanism is a hybrid version of a serial (open-loop kinematic chain) and a parallel (closed kinematic chain) mechanism, combining their advantages of a large range of motion and all springs connected to the base. The linkage moves in a vertical plane by means of revolute joints perpendicular to the plane. This plane is rotatable about the vertical through the fixed pivot by means of a vertical revolute joint. Thus, three degrees of freedom have been obtained so that the end point of the mechanism can follow the patient's arm (Fig. 1, top row). The connection mechanism to the fitting contains additional rotational degrees of freedom to allow for different orientations of the forearm relative to the mechanism.

A prototype was made, primarily to validate the newly found solution principle, which had a combined friction and balancing error of 5% of the maximum support force of 23N.

B. Mark II: Clinical Prototype

To avoid the interference with the wheelchair and its arm rest that was present in the first prototype, the parallelogram mechanism was modified. In fact, the other branch (solution of inverse kinematics) was selected, where the two parallel links are going up, over the arm rest, and the end link goes forward to the interface with the user's arm (Fig. 1, middle row). For this linkage, the workspace was optimized, aiming at a compact mechanism that is mounted at a convenient location. The resulting link lengths are 280 mm for the base

Fig. 2. Prototype of the arm support, Mark I. This prototype was manufactured to validate the principle of full balancing while only partially supporting the arm mass [2]. Top: This subject (SMA II) is capable of raising her arm. Bottom left: Also moving out is possible. Bottom left: This subject (SMA I) has difficulties in raising her arm.

link and 320 mm for the end link [17].

The linkage was balanced by springs that are all located around the base joint of the mechanism in the box. This box also contains an adjustment mechanism that allows to change the support force by a switch operated electric motor [18].

The adjustable balancing mechanism incorporates a transmission to overcome space limitation problems for the springs. Due to low friction requirements, a rolling twin cam was selected. Fig. 1, middle row, shows the principle for one link. Two of these, one for each segment, were implemented in such a way that they can be adjusted simultaneously.

The resulting balancing errors are mean errors of around 3% and maximum errors of around 13% for all of the three cam shapes [18].

C. Mark III: ARMON

For the final design it was decided to employ another balancing principle, combining low friction with theoretically zero balancing error. One special arrangement with multiple pulleys was suggested by Soethoudt (Fig. 1, bottom row, cited in [16]). The principle makes use of a spring that is configured such that the string segments wrapped around the pulleys (of equal radius) add up to (a multiple of) one pulley circumference for any position of the link, so as to provide perfect static balance in theory [19]. This arrangement was applied in the arm support, where for each of the two springs one such pulleys-and-string system was incorporated in the design, and where the springs were not fixed to the base but placed inside their respective base

Fig. 3. Prototype of the arm support, Mark I, showing some problems encountered with it: Fitting design: (left) Interference between mobile arm support and fixed arm rest prevents movement from the hand to the face, (right) dead point where control is lost and the arm is locked.

links. This resulted in a much smaller base box (Fig. 5).

The workspace in terms of hand position ranges in up/down direction from well below the fixed arm rest to forehead level (Fig. 6). In sideways in/out direction, the users can move across their lap or wheelchair table, while moving out laterally is restricted only by the natural constraints of the user's arm. In addition, the elbow can be moved fore/aft over the entire length of the fixed arm rest.

It was decided to incorporate an adjustment option for the balancer down to a support force of zero (i.e. until the springs only balance the weight of the mechanism itself). This allows users to 'switch the device off', i.e. fixate the mechanism relative to the wheelchair. To further eliminate undesired mechanism motion, a friction brake was incorporated which is automatically engaged as the balancer adjustment approaches zero, for instance to avoid a floating arm when riding the wheelchair.

Another mechatronic feature that was incorporated is an automatic leveling function. This device can be overruled by two electric switches: one for tilting the device forward and one for tilting it backward. This can be used to generate force in the respective directions, for instance to press an elevator button, or to work against contractures.

When properly adjusted, the force needed at the interface to set the mechanism in motion (static loads, not considering tissue-induced forces) is around 0.2 N, throughout the range of motion, regardless of the load setting, and regardless of the direction of motion. This suggests that this 'balancing error' is mainly due to friction, rather than due to the balancing mechanism itself.

III. USE IN DAILY LIFE

While formal user studies are being prepared, the aim of

Fig. 4. Prototype of the arm support, Mark II. This prototype was manufactured to evaluate the design in a home or clinical setting by trying it out on a larger number of patients (around 16) so as to gain user feedback [17].

this section is merely to report on preliminary user experience, so as to see whether design choices that were made in the development stage appear to have made some sense and to reflect on possible improvements. The three generations will be discussed in separate subsections.

A. Mark I: Proof of Concept

Home visits were performed with three users. All of them were capable of lifting their arm against gravity (Fig. 2), and found the concept promising. In particular the esthetics (the device is compact, placed below the fixed arm rest, and only part of the distal link is visible), and the intuitive control (no joysticks or similar required), and natural feel were appreciated. This result demonstrates that the CCM-approach works well, i.e. that the shoulder may be used to carry part of the upper arm weight.

In spite of this result, some improvements were found necessary. Firstly, the distal link of the mechanism interferes with the fixed arm rest (Fig. 3, left). A curved distal link provided some but insufficient relief. Consequently, it was difficult to touch the central part of the face. Secondly, also due to the curved distal link, the CCM was not located exactly at the centerline of the distal link, but slightly closer to the user's body. This resulted in unbalance that proved to be problematic, the more so when the distal link deviates more from a vertical position (Fig. 3, right). Thirdly, in weak patients, the combination of the balancing error and friction proved to be too great, even though ball bearings were used throughout the mechanism (Fig. 2, bottom right).

B. Mark II: Clinical Prototype

The second prototype was tried out by several users (Fig. 4). They were asked to perform several ADLs with the device. Their opinion was generally very positive. Some discomfort was experienced due to slight mechanical deficiencies of the prototype. Nevertheless, the results were promising. The strongest of the subjects – generally incapable of bringing their hands to their mouths – were able to drink independently, directly from a cup or glass, not with the use of a straw. The weakest of the subjects was able to put on and off her glasses, and eat small portions independently.

Several improvements were suggested, including faster adjustment, improved fitting procedure, and a narrower design that facilitates passing through doorways.

Fig. 5. The arm support Mark III, called Armon [19]. On the left the product in a semi-see-through view, showing the springs inside the base links and the balancing adjustment actuator in the box; on the right the product as fitted to a wheelchair.

Fig. 6. The Armon in lowest and highest position. This range is sufficient for several important activities of daily living.

C. Mark III: ARMON

The device has become available recently and several dozens of patients have been fitted so far. Three of them have been using (beta versions of) the device for about a year on a continuous basis (6-10 hours per day). The others have been using it for up to eight months. Some of these also use the device continuously, others use it only at home for eating, drinking, and keyboarding. All users are capable of reaching their face and their lap or wheelchair table.

Table 1: Overview of three example users

User	1	2	3
Gender	V	V	M
Disease	SMA I	SMA II	Becker
Prior experience	Manus	Top Help	none
Side of arm support	R	R	R
Duration of use (months)	14	14	10
Daily use (hours per day)	10	8	6

Table 1 lists three example users of the Armon who report in this study. Pictures of various activities of daily life are given in Figs. 7 and 8. User 1 reports that the Armon allows her to put on her glasses, do her face, and tickle her nose. Furthermore she is able to drink independently (directly from a cup, not with a straw), and to operate lift buttons and prepare food in a microwave oven. Important for her is that she can eat pre-cut food independently: she no longer needs to be fed when eating out pizza with friends. Also she can take medication by herself. She reports no interference of the mechanism with the wheelchair or her arm, but she cannot reach far out to the side. User 2 is relieved that she is for the first time in years able to eat and drink independently. She emphasizes that it is very difficult for someone else to perform elementary intimate tasks such as putting on her glasses (either skew, against eyelashes, or fingerprinted) or scratching, and is happy to be able to do this herself now. She finds the range of motion sufficient in vertical direction, but is not able to reach out to the side further than just enough to let her arm hang down next to the wheelchair, comparable to user 1 (Fig. 6). Several ADLs have become possible, including raising a glass (toast), picking up her postal mail from the mailbox, and shake hands, which is important to her. User 3 uses the Armon mainly outside, to independently operate a public cash machine, play chess, smoke, and comb his hair. He also uses it to dine independently, both at home an out, to operate elevators, to put money and paperwork on the counters of shops and ticket office windows. He has also fed his baby nephew with the help of the device.

User 1 is pleased that there is no perceivable frictional threshold, as there was in the earlier models. A small push sets her arm in motion. Due to her muscular weakness, she makes frequent use of the adjustment function, although the nominal setting provides sufficient balance to allow her to move also without readjustment. User 2 remarks that she can perform goal directed movements accurately and securely.

The general appearance is widely and highly appreciated. User 1 reports several occasions where people did not until after half an hour notice the arm support. User 2 also finds it inconspicuous and pleasing, which is important for her. From the fact that people hardly if at all notice that she is using an aid she concludes that the device must provide a natural motion pattern.

Another user used to have two suspension-type arm support devices (strings from an overhead pulley construction) and now has two Armons. He reports that people used to first see the devices and then him, which is now inverted, much to his pleasure.

Fig. 7. The Armon in various activities of daily living.

Since no separate control is needed for the motion, the users can work with the device almost immediately. Initially they still work a lot with their body, but gradually they learn to do more and more with their arms themselves, thus discovering new possibilities continually. Also the operation of the switches requires little learning effort. In approximately a day the users got accustomed to operating the switch unit. User 2 remarks that she at first used the balancer adjustment a lot more than presently, as she more and more relaxes her whole body when moving her arm with the device. The brake, which is engaged when the support force is trimmed completely down, is used for wheeling outside, when traveling by taxi or train, and sometimes at home as well.

IV. Discussion

In the scope of this paper it is interesting to review several users' subjective appreciation of the device, in particular users who have used all of the prototypes. User 1 gives the following account: "The first prototype lifted my arm for the first time. I could get my elbow off my table, which was a marvelous experience. That, however, was basically all I could do with it, the device was not functional. It also required too much effort: some help was needed, even though a little bit, to reach my face, while picking up objects was not possible because the balancer was not adjustable. Furthermore, the device hit my wheelchair all the time and my arm did not stay put in the interface. The second prototype was not very reliable, which makes judging is a little difficult. At least the interface was a lot better than in the first model. Although a balancer adjustment was built in, it had to be operated by one of the engineers, which was very cumbersome. The box stood out to the side considerably in some arm motions. In spite of all this, it did allow me to perform some motions, but trunk movements remained required for functional tasks. User 3 adds: "Once it worked and was adjusted properly, it allowed me to eat candies and drink a glass of water. The range of motion was considerable". User 1 again: "The third model, Mark III, is a different story. I never once slid out of the interface, adjustment of the balancer is very easy, the availability of the brake, and the negligible resistance are great improvements. Furthermore, the fact that it looks good, hardly visible, is a big plus". User 3 does not use the brake a lot and would not mind a greater range of motion.

As will be clear from the above, the development of the arm support has benefited greatly from the user experiences, however preliminary. The design iterations functioned as step by step evaluations of ideas and embodiments. Apart from encountering unforeseen problems at an early stage in the development, the design iterations also allowed us to profit from unforeseen bits of luck. It also helped a lot in obtaining feedback from users. Without a device to try out, it is difficult for users to specify design requirements.

V. Conclusion

The development and preliminary user experiences were presented in this paper to show their intimate relationship in that each design iteration raised new feedback for the design and each prototype stimulated more detailed feedback. Three stages of the design were discussed from an engineering and a user perspective. The iterative design process was found very important for obtaining detailed user opinions that were used to adjust the design specifications and to modify the design based on their feedback. As a result, a mobile arm support was developed in a relatively short time span. The fact that it is now available under medical insurance cover will allow us to do formal evaluation studies in the near future.

Fig. 8. The Armon in various activities of daily living.

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