Design of a Dynamic Arm Support (DAS) for gravity compensation

Gijs Kramer, GertWillem R. B. E. Römer, and Harry J. A. Stuyt

Abstract—**The Dynamic Arm Support, or briefly the DAS, is a new medical device that serves to compensate for lost arm function of the severely disabled. The target group suffers from insufficient muscle force to move its arms over the usual Range of Motion (RoM). The purpose of the DAS is to assist its user during Activities of Daily Living (ADL) by eliminating gravity acting on the upper limb and enabling the limb to move freely. The development of the DAS is presented and discussed, focusing on the modular parts, working principle, unique features, and technical performance as well as results for the target group.**

I.INTRODUCTION

THE DAS is a new medical device that serves to compensate for lost arm function of the severely disabled. The target group suffers from insufficient muscle force to move its arms over the usual Range of Motion (RoM), but sufficient remaining hand function for grasping during ADL-tasks. Typical users suffer from Spinal Muscular Atrophy (SMA), Amyotrophic Lateral Sclerosis (ALS) or Duchenne Muscular Dystrophy (DMD), in such a stage of progression that the hand function suffices for grasping objects. Since other assistive devices, such as the Assistive Robotic Manipulator [1] (ARM), are available for users in a next progressive stage of the aforementioned diseases, some hand functionality can be assumed for the DAS. An arm support like the DAS utilizes the residual muscle capability to the fullest and therefore it maximizes independence, and is expected to provide exercise as well.

Examples of commercial devices to support the user's arm exist, such as Focal's TOP [2] and MicroGravity's Armon [3] (both companies are based in the Netherlands), Neater's Arm Support (UK) [4], the Radial Arm/Balanced Forearm Orthosis (USA) [5], and even the ZoncoArm (USA) [6]. Though successful for their specific target groups, these products can be improved. According to e.g. brief user and trial user interviews [7]–[9], and conversations with experts in the field - e.g. rehabilitation technicians, a need exists for a newly designed device, which provides a compensation force that enables up/downward movement of the arm by small muscle force, and yet of simple form, fitting to the user and his/her RoM and to the electric wheelchair as well.

II.DEVICE SPECIFICATION

The basic product idea consisted of a sleek and tightly fitted linkage on a gravity balancing unit that was inconspicuously mounted on the wheelchair. This modular approach enabled separate development of modules, and use of commercial products, such as the lift-unit of the ARM [1]. The resulting modules are displayed in Fig. 1. An explanation follows in the sections below.

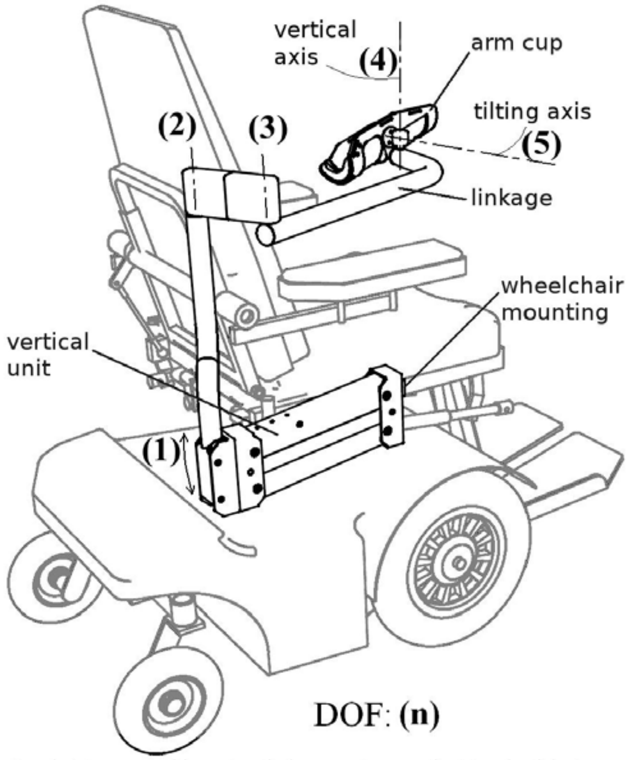

Fig. 1. DAS general layout and placement on an electric wheelchair

The main requirements for a new dynamic arm support were:

1) A gravity compensation of the user's arm weight - that is, a constant upward force over a vertical range of a single so-called *vertical unit* with one Degree Of Freedom (DOF). Compensation force is to be adjustable by the user,

2) An *arm cup* which supports the total human arm at its composite Center of Gravity (CoG), which is located in the user's lower arm [10],

3) A *linkage* beside the arm of the user instead of underneath, starting from the arm's composite CoG to behind/beside the shoulder, yet smoothly curved and to enable passing through a doorway,

4) A RoM which enables the following (at least):

  - eating/drinking; bringing the hand to the mouth;

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G. Kramer (corresponding author), G.R.B.E. Römer and H.J.A. Stuyt are with Exact Dynamics BV, Didam, The Netherlands (phone: +31(0)316334114; fax: +31(0)316331327; e-mail: g.kramer@exactdynamics.nl).

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- the lower arm in the arm cup in resting position; on the wheelchair's arm rest;
- no singularities of the linkage encountered in the user's workspace;
- no collision between user and device - especially when raising the hand while lowering the elbow;
- no collision with the wheelchair - especially in low position;
- the hand touching the shoulder and elbow of the other limb;
- low possible hand position - lower than a horizontal lower arm - for e.g. touching the knee;
- use of the arm support on a wheelchair equipped with a tray;

5) No or minimal adaptations to the wheelchair should be necessary other than the mounting bracket; nor the need to dismount the wheelchair's arm rest as the user may want to push himself/herself up to sit straight,

6) An inconspicuous device that resides out of the user's Field of View (FoV) as much as possible,

7) A linkage offering all DOFs to the lower arm except vertical translation (which is the compensated DOF) and rotation about the length axis (pro/supination),

8) Options for individual adjustment and fitting of the DAS to the user; e.g. the fixing of the lower arm by either straps or using fixed cushions at the elbow.

III. DESIGN PROCEDURE

The development from basic product idea to the current tested prototype took about 12 months. A stakeholder analysis according to the USERfit method [11] was performed.

The first mockup essentially consisted of an adapted ARM lift-unit with a simple elbow support connected to it. This was used to assess the basic placement on a wheelchair and the suitability of these modules.

Next, a function model was manufactured to test gravity compensation, its vertical stroke, and horizontal RoM. The modular approach ensured principal development of one part, while another module was already tested after manufacturing. Statistical biometric data [12] and ADL-trajectory data [13] were used for dimensioning the horizontal and vertical stroke of the DAS. The aimed target group consists of 95% of all people of ages 6 and up. By using a man-model that has body dimensions corresponding to the 95th percentile of 20 to 30 years old Dutch population, several ADL-positions such as in drinking or placing the arm on an arm rest were studied. Of course, since a.o. separate body dimensions are correlated, the man-model does not correspond to 95% of the 20 to 30 year-olds, but the target group was covered since it includes (smaller) children and 30-plus year-olds as well.


Fig. 2. The DAS first function model with mainly a top view on the linkage. This photgraph is composed of various user arm positions put together.

The linkage of the first function model proved to protrude too much, see Fig. 2. The gravity compensation and its adjustability however, were promising in magnitude and stroke. Several following linkage mockups and redesigns resulted in a linkage shape that is tightly fitted to the user and his/her wheelchair.

Both technical performance and product ergonomy were improved in the second - current - prototype. It incorporates the optimized linkage shape. A study of electrical wheelchairs popular in the Netherlands - and suitable for ARM use - ensured a device layout even around most wheelchair arm rests that extend to the back of the wheelchair.

The current pre-production prototype contains several modifications for better adjustability during - and ease of - assembly, better linearity and lower friction in gravity compensation. The final model is currently being manufactured.

IV. DEVICE ARCHITECTURE

The DAS consists of modular parts as mentioned. The general layout of the device and location on a wheelchair are depicted in Fig. 1. The basic principles of the DAS are similar to [14]–[16], but with the DOFs providing horizontally free movement at locations designed for wheelchair use.

A. Vertical unit

The DAS compensates gravity (to an adjustable constant amount) in only the upward direction, resulting in a balanced human arm. To this end, the weight of the total system - the DAS with a human arm in it - is compensated by a spring system with an indifferent equilibrium, according to [14].

This is contained in the *vertical unit* (see Fig. 1 and Fig. 3). With a zero-free-length spring of constant k, a compensation of magnitude mg is achieved under (semi-)static conditions, when the mechanism dimensions are L, a and r_a. Mass m then has indifferent equilibrium in a gravitational field with acceleration g.

$$r_a a k = m g L \tag{1}$$

Note that the compensation of mass m is equal over height. This is bound to actual mechanism dimensions and the range over which variables truly are constant, such as g and k. Other errors may be introduced in the actual selected device components; for instance, roller bearings may endure friction that depends on the radial load, thus decreasing the compensated weight at positions where bearing load is higher. These errors are not considered in detail in this article.

The DAS has a high force capability in a small available space, as shown in Table 1. This is possible by high-strength spring material, high spring constant, and compact spring coil mounting. The maximum of available space over the entire length of the mechanism is used for this purpose and the spring force is transferred to the needed location - shown in Fig. 3.

High compensation force was required, since heavy user arms of the 95th percentile of normal people were not to be excluded. The maximum total arm weight to support was estimated by extrapolation at 5 kg, corresponding to a person with the target group's maximum body length [17], [12]. This also gives design latitude for the device's own weight and the device capacity to lift large weights besides the user's arm. A possible low compensation force that allows an unloaded DAS to remain in the bottom position - easily accessible for the user - was also required.

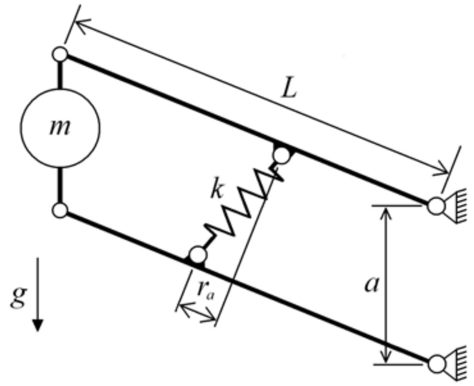

Fig. 3. Weight compensation principle of the DAS

Since spring constant k is large for high compensation force and small construction size (with fixed L), the adjustment mechanism needs to be more accurate, rigid and without play as k becomes larger. This is because every deviation from exact adjustment system geometry - r_a and a in (1) - is multiplied by k to result in a compensation force error of a larger magnitude. The DAS has a compact, high-force actuator in the compensation force adjustment system.

The external housing is of proven design of the ARM; sleek and compact, and safe with respect to e.g. entrapment of fingers between the moving parts.

TABLE I
DAS PROPERTIES

Property	Explanation
Mounting	On electrical wheelchair
Purpose	ADL assistance
Gravity compensated DOFs	1 (vertical)
Arm cup/linkage DOFs	4 (leaving hand pro/supination open)
Compensation force	0 N to 50 N
Horizontal stroke	128 cm side to side
Vertical stroke	26 cm
Safety measures	Fail-safe electronics/shock-dampers/breakaway linkage/smooth force adjustment
Total weight	4.9 kg
Main dimensions of vertical unit	51 mm × 128 mm × 357 mm
Actuator power supply	24 VDC (e.g. wheelchair battery)
Means of operation	2 single switches, e.g. wheelchair buttons or mini-jack plug switches

B.Linkage system

A linkage - set of two tubes - that is placed on top of the vertical unit, guides free movement and rotation of the arm cup in the horizontal plane through its three DOFs (2, 3, and 4 in Fig. 1). The last DOF (5 in Fig. 1) is the tilting axis of the arm cup. The rotation of the user's lower arm (pronation/supination) principally allows the user's hand to assume an arbitrary position and orientation within the user's natural RoM. The number of horizontal links is two, to have properly defined kinematics of the linkage and a minimum of singular points, which are not to be reached within the user's RoM. This also prevents e.g. the user's elbow from colliding with the linkage, unexpectedly or otherwise.

To allow an arm position low on a working tray, the lower arm is supported from the side, out of the user's FoV. The two-link linkage has its base joint near the user's shoulder. This is accomplished by tubing that is able to break away in case of collision and is adjustable for exact placement of joints. From the user's shoulder, a horizontal linkage is required, when it is considered that it should wrap tightly around the user - without colliding - and also should remain above wheelchair's arm rest height to prevent from obstruction with the arm rest.

The DAS mounting and linkage layout allows use of the seat lift of the wheelchair, but also reclining of the back rest. However, the DAS is targeted for use in active user position [18]. No wheelchair parts (e.g. arm rest) have to be removed to mount or use the arm support on the chair.

The dimensions of the linkage was determined by using the man-model mentioned in section III, but also a similar model of a 6 year-old to ensure fitting on the smallest persons in the target group. The following arm positions were used for optimizing linkage dimensions:

- eating/drinking position;
- resting position on arm rest;
- in front of belly to medial side;
- far outstretched to lateral side;
- outstretched to front;
- relaxed on working tray, as far inward as comfortable (for e.g. passing doorways)

Considering the length of the tubing and possible arm weight, the linkage has been constructed to be robust, but made of round tubes to appear slim [19], yet not frail. Secondly, minimum weight was strived for in design. The latter was not necessary for improving the force capability of the DAS, since provides sufficient compensation force for its own weight, but to maintain a low total weight on the wheelchair.

Finally, the linkage can be fixed horizontally on e.g. the working tray or arm rest, or easily dismounted from the vertical unit when unused.

C.Arm cup

Tilting about axis 5 in Fig. 1 is allowed because the total arm is supported at its CoG; therefore the lower arm should be fixed to the arm cup. Several possible ways are open to individual preference when using the DAS. Various straps, padding, and/or elbow supports can be used, or even none at all. The DAS has an optional retractable elbow support that allows outstretching of the arm, yet supports the lower arm when positioned vertically. The current prototype incorporates a single size arm cup, with additional padding for various arm sizes if needed.

Fig. 4. DAS prototype with arm cup including straps on a wheelchair

From arm weight data [17], composite CoG positions of human arms were derived. However, by flexing the wrist - if the user is able to, the composite CoG position will slightly shift. This gives a measure for fixing accuracy (several millimeters) of the lower arm in the arm cup. A solid elbow support is therefore very usable in some cases even though it may cause the CoG to shift; especially when joint movement is limited by contractions in the user's elbow.

The arm cup has sufficient size for small surface area pressure [18], and ventilation holes. The arm cup is a single self-carrying part with a bottom thin enough to approach a tray closely. The arm cup's position relative to aforementioned tilting axis is accurately adjustable to ensure easy tilting of the lower arm and resulting in a larger vertical range of the hand.

D.Man-machine interface

The DAS contains dedicated electronics for operation by means of several possible input devices. Only two signals are needed – for instance from two switches. It serves for operating the compensation force adjustment system (increase/decrease only). Other functions of the electronics are for safety: prevention of overheating the actuator, reverse polarity protection, and prevention from wrong input from the input devices. Other possible input devices are for instance: buttons of a wheelchair or the output of a scanner, such as HMC's Easy Rider [20]. For the sake of future development, an input for a third switch is present, including a rudimentary menu-structure, for two arbitrary other functions (to be assigned). The electronics are included within the DAS vertical unit.

V.TEST RESULTS

A.Technical verification

The force capability and linearity of the DAS were tested by mounting the DAS vertical unit on a tripod and attaching ballast and a scale on top. The upward compensation force was determined for small constant speeds upwards and downwards to ensure semi-static conditions. The results were corrected for the ballast in testing and the weight of the DAS linkage and arm cup, to obtain the compensation force over vertical position (Fig. 5). The hysteresis in the linkage and arm cup due to dissipated elastic energy were neglected, as well as the dynamic behaviour of the total DAS. The test was

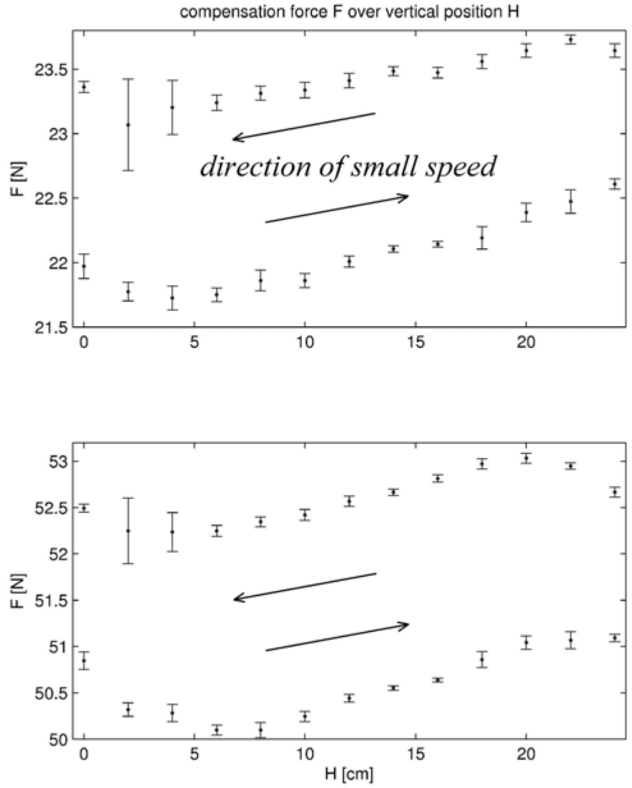

Fig. 5. Compensation force *F* of the DAS over vertical unit position *H*. Standard deviation is included. Significance of compensation force F: 0,05 N, significance of height H: 0,1 cm.

performed for two compensation force values: first at 51,5 N, and secondly at 22,7 N for supporting a common arm weight.

As can be concluded from Fig. 5, the system exerts different forces for both moving directions (up/down) at a single vertical position and compensation setting. This is the characteristic behaviour of virtual play. The general term is hysteresis, which can be observed in Fig. 5 as the differents set of points for upward (bottom set in both the graphs) and downward (upper sets). The energy in the compensation system that is dissipated during movement will not be recovered for movement in the opposite direction, and therefore friction - e.g. in the mechanism pivot bearings and the mounts of the spring - decreases the working, as the test results show. Some stick-slip helps to maintain a balanced position, but this in general is not an objective of the DAS. Another example of disadvantageous friction is the elastic deformation of the spring, where energy is also lost as heat. The magnitude of hysteresis in the DAS is ±3,3% of the compensated weight. The necessary muscle force to move downward after initial upward movement is 1,5 N maximum at a height H of 4 cm, when the system is set to compensate common arm weight. This corresponds with the order of magnitude of downward user force in the ballpark figures in [21], however the prototype may not be usable for the very weak users and improvements are necessary.

Furthermore, a nonlinearity of compensation force over height exists. In general the compensation force is larger when the system is in a higher position. The nonlinearity can be attributed to phenomena such as dimensioning and machining errors, which are easily corrected. Furthermore, it appeared that an inaccurate setting of the system in assembly is a clear cause of nonlinearity, and in the end-of-stroke shock dampers have their apparent effect. In addition, several other components have non-ideal and/or position-dependent behaviour that can be remedied. Examples are again the spring, which can always be improved in linearity, and the roller bearings with load-dependent friction.

The maximum compensation force however is sufficiently large, also for lifting large weights up to 5 kg. The relative total error in compensation is at worst 4,4% for the lowest preset compensation force (for common arm weight), which is promising because room for improvement is apparent. A gravity compensation error smaller than 2% seems easily attainable.

A simple timing experiment shows the adjustment time from minimum to maximum compensation force. At first the time to reach maximum (50N) compensation force from zero, is 9,2 s. Zero compensation force from maximum is reached in 8,9 s. The corresponding mean speeds are 5,4 and 5,6 N/s respectively.

TABLE II
TRIAL USER DEMOGRAPHICS AND PROPERTIES

	User 1	User 2	User 3	User 4
Gender	female	male	male	female
Age	7 y/o	10 y/o	19 y/o	31 y/o
Living situation	with parents	with parents	with parents	independent
*Length of lower arm**	17 cm	21 cm	27 cm	24 cm
*Arm weight***	734 g ± 20 g	1060 g ± 20 g	1234 g ± 50 g	1750 g ± 50 g
Dexterity	right-handed	right-handed	right-handed	right-handed***
Clinical picture	SMA	SMA	DMD	SMA
Wheelchair type	Permobil Playman	Permobil Playman	Ligtvoet Leader	LMD

Data correspond to trial user's left arm.

*From elbow to wrist (processus styloidus ulnae).

**Measured at total arm's composite CoG approximate location; variation is due to inaccuracy of scales and muscle force.

***User's left hand is the most active for e.g. steering the wheelchair and using an arm support.

B. User validation

The user validation was performed at the St. Maartenskliniek, Nijmegen, the Netherlands, and at the home of the third potential user. The main goals of user validation were:

1. Evaluate RoM
2. Obtain user feedback
3. Investigate detailed items below for:
    a) finishing basic DAS version
    b) further development

The trial user group of two adults and two children represented some extremes of the target group, in hand function, age and body size, see table II. Hand function varied from relatively good (but not able to lift arm or to push buttons or to drink) to very weak. This variation gives a good measure for usability in the total target group [19].

First the user's arm function was assessed and an interview was taken to determine which tasks the user would like to perform with the DAS. The DAS was placed on a tripod next to the user's wheelchair. After a brief explanation of the device, and an accurate fitting of the arm cup to the user's lower arm, the user was given full control of the DAS. Then a few specific tasks such as drinking were executed, when relevant.

The performed tasks per user are:

User 1: drinking from a mug, reaching forward, scratching her head, typing on a computer keyboard, and playing a game of "Connect 4" [22],

User 2: scratching the top of his head,

User 3: touching the face, scratching the back of his head, and picking up something from a low table,

User 4: drinking from a mug, reaching to the side, scratching the top of her head, and writing.

The DAS showed sufficient RoM for all users. The stroke from front to back was the first limit eventually encountered, but only when the DAS was set up incorrectly. The linkage will need to be adapted slightly, to give a larger margin of positioning error. The vertical and side-to-side stroke are sufficient. Elevator buttons were accessible for User 4, as she desired. The high vertical position allows all users to scratch their head, and the possible low position was also deemed a big advantage over other devices. Any vertical position in between was reachable when the gravity compensation was adjusted correctly.

The maximum compensation force was sufficient for all users, and additionally lifted objects posed no problem. All had relatively lightweight arms, but the DAS did also support the heavier arms of ergotherapists that evaluated the DAS.

The main problem during user validation was the hysteresis through friction and nonlinearity in the vertical unit, which is clearly detectable in the device and easy to improve by replacing several components. Although the hysteresis of ±3,3% (see previous section) is small, three out of four potential users experienced it. Hysteresis led to sudden movement downward of the limb when the compensation force was decreased by the user. Second, two out of four users had difficulty tilting the lower arm downwards with a fixed compensation force, since the limb's composite CoG has to move downward for this and these users did not have enough force capability. The maximum downward force of the strongest user (User 3) of the three users who encountered hysteresis, is of a magnitude of about 2,2 N, and he had only a small trajectory of about 10 cm over which he could move his arm downward without decreasing the compensation force. The adjustment of the compensation force however was - although too fast and therefore inaccurate - easy to learn and use intuitively. The first user needed only a single instruction before moving her arm up and down to play a game of Connect 4.

It should be noted that the User 2 has such strong contractions in his elbow, and unwanted backward position due to a too small size wheelchair, that his joints would not allow any other arm position than directly in front of his body and face. He assessed the DAS as not useful for him at that time. The other user opinions ranged from relatively positive to enthousiastic. The arm cup fitting did not give problems in terms of comfort, but the adult-sized arm cup (fitted by using padding) proved too bulky for small children. In general, the retractable elbow support was favoured over the rigid one, and it is currently being designed for production as well as smaller sizes arm cup.

The user's wheelchairs were all possible to mount the DAS on, although this is not a trivial task considering the very large back wheels of User 4's wheelchair, which was of an old type.

VI.CONCLUSION

An assistive device referred to as the DAS has been newly designed. It provides a compensation force that enables up/downward movement of the arm by small muscle force, and is yet of simple form, fitting to the user and his/her RoM and electric wheelchair.

The DAS is - at this time of writing - being improved for gravity compensation with smaller errors, because hysteresis and nonlinearity causes limitations in use for some potential users with very small muscle force. User validation also revealed that the DAS gravity compensation is definitely usable for part of, and the RoM for all tested potential users. Applicability for the total target group is expected after a.o. improvement on hysteresis. The DAS is currently being designed for production.

For future work, a brake in the vertical unit is considered to lock a certain vertical position. This brake will be switched on/off by the user by means of a third button.

Finally, an automatic balance system accounts for variable wheelchair seating angles which may be changed by the user, whereas the DAS should remain perpendicular to earth for ideal use. Both the brake and the balance system are optional.

VII.ACKNOWLEDGMENT

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