# Freebal: dedicated gravity compensation for the upper extremities

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***Abstract*— In most upper-extremity rehabilitation robotics, several components affect the therapy outcome. A common component is gravity compensation which alleviates upper-extremity movements. Gravity compensation by itself could improve motor control further or faster, separate from other effects of robotic therapy. To investigate the rehabilitation value of gravity compensation separately, we created the dedicated gravity compensation system, Freebal.**

**The sling systems with ideal spring mechanisms in the Freebal are well suited for providing compensation forces. The device has steplessly scalable forces, a large range of motion with constant compensation forces, independent control of the compensation of the lower and upper arm, and low movement impedance. It also does not need external power, force sensors or active controllers. Finally, the Freebal can be easily moved, serviced and used in arm rehabilitation with either sitting or standing subjects.**

## I. Introduction

Patient-friendly robotics for upper-extremities rehabilitation are used as diagnostic and therapeutic aids for a wide range of disabilities. For stroke patients with affected motor control of the arm, improving control is important to regain functional abilities. Current robotic devices try to accomplish this by a number of different rehabilitation theories. For example, the MIT-Manus [1] (partly) assists arm movements during tasks execution, the MIME [2] mirrors the movement of the unaffected to the affected arm, the ACT$^{3D}$-training [3] tackles undesired abnormal muscle couplings and the ARMin [4] motivates patients by interacting with virtual environments. Overall, these robotics make rehabilitation therapy more challenging for the patients and less labor intensive for the therapists, and they provide the physicians, therapists and scientific community with more objectively gathered data.

According to systematic reviews, the new robotic therapies are at least as good as regular therapy for stroke rehabilitation. Van der Lee et al. [5] tentatively concluded that the type of therapy matters less than the exercise intensity. Several approaches with and without robotics resulted in roughly the same effect when the level of intensity was matched. They did indicate that using robotics may be a useful way for increasing the intensity. Platz [6] found evidence for superior treatment efficacy of task oriented, motor-relearning

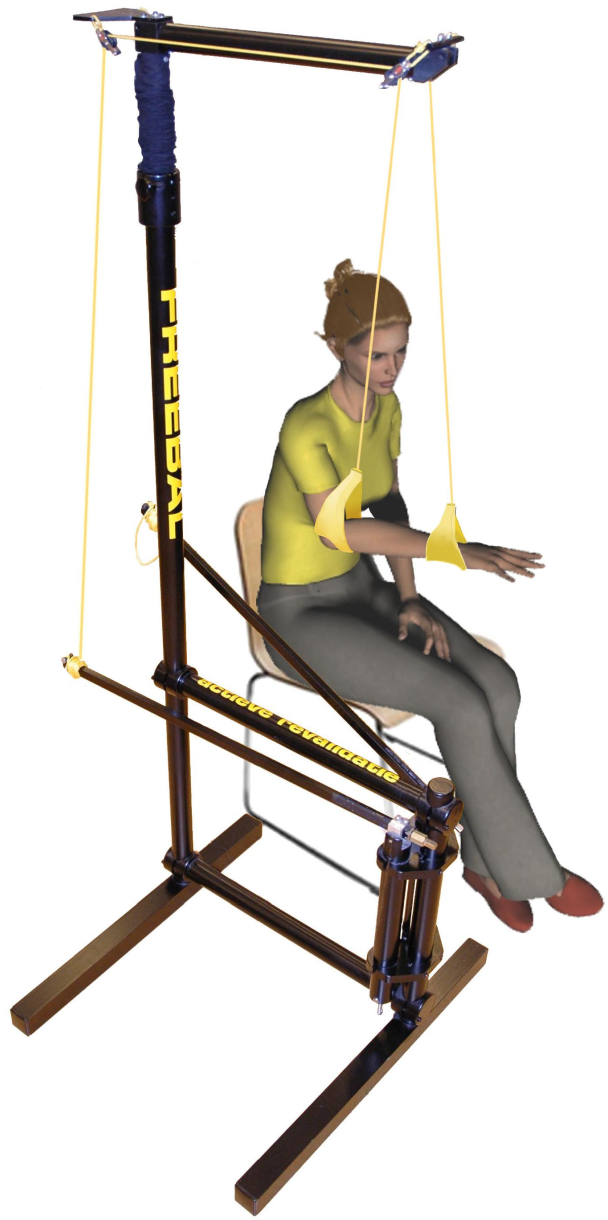


Fig. 1. Freebal gravity compensation system, which generates the compensation force with an almost inertia-free ideal-spring mechanism (see Fig. 2). The wrist and elbow of subjects are hung in the two slings supports of the Freebal. For graphical reasons, the Freebal is here shown with the lowered overhanging beam instead of the normal $3.5\ m$ above ground level.

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programs and giving different patient subgroups specific training strategies. They also found a higher intensity of motor rehabilitation resulted in an accelerated, although not necessarily better, motor recovery. Finally, a recent review from our project group [7], concluded that robotic therapy of the shoulder and elbow improves motor control of these joints, and probably more than conventional therapy. Consistent influence on the functional abilities of the patients was not found.

The conclusions agree with systematic reviews on regular therapy for the upper extremities; intensive and task-specific exercises, consisting of active, repetitive movements, give the best results [8], [9], [10]. This follows the main principle of motor learning; the improvement in motor-control performance is directly linked with the amount of practice done [11]. Measured on clinical scales, however, a significant improvement in motor control does not necessarily result in a higher functional ability.

In most rehabilitation robotics, several components affect the outcome results. Often, the therapy is simultaneously made more intensive, more supportive, and more motivating for the patients than is possible with regular therapy. More repetitions per session, movement assistance via external actuators, and involving and stimulating virtual environment, all influence the rehabilitation process. But in most efficacy studies, the effects of the individual components are not reported. This lumping of components may explain why the type of robotic therapy has so far made little difference in the systematic reviews; a common component like the increase in intensity could be far more important than any of the type-specific ones.

A common component in rehabilitation robotics is anti-gravity support or gravity compensation to alleviate upper-extremity movements. Many of these gravity compensation systems are fully or partly integrated in the main design of the robotics. The MIT-Manus supports the lower arm with a stiff, vertically-hinged connection to the device-hand interface. The GENTLE/s [12] links the wrist to a haptic device, while the arm is hung in two supporting slings. The ACT$^{3D}$ uses a 3D haptic robot to support the weight of the arm. Before, the same group placed the lower arm on a lightweight slide moving over an air table [13]. Finally, the ARMin uses both balancing counterweights as computer controlled compensation via exoskeleton actuators. Different compensation mechanisms influence the arm movements in different ways, but by making the movements easier for the patient, all the mechanisms are also able to increase the rehabilitation intensity (more repetitions per minute) and duration. Gravity compensation by itself could improve motor relearning further or faster, separate from the effects obtained by the other implemented rehabilitation theories like motion assistance or mirrored movements.

A couple of devices designed specifically for gravity compensation exist, like the Swedish Helparm (also known as Helparm, Swedish Sling, Deltoid Aide or OB Helparm). With these and similar devices, the weight of the arms is supported by overhanging slings, counter balanced by either masses or springs. Both have their disadvantages; masses double the vertical movement inertia of the arm, and directly-connected springs make the amount of gravity compensation strongly dependent on the vertical arm deflection and can introduce uncontrolled oscillations.

To investigate all aspects of gravity compensation, we deduced we needed scalable and independently compensation for the upper and lower arm with maximum freedom of movement and minimal impedance. A simple, mechanical device has obvious advantages in cost, use and maintenance over more complicated mechatronic solutions. Such a device did not exist at the time, thus this paper describes the development and evaluation of our dedicated gravity compensation device, the Freebal.

## II. Requirements and Implications

End-point controlling systems, exoskeletons and balancing sling systems are three groups of devices which can interact with the human body and have been used in the past for gravity compensation. To achieve the requirements of scalable and independent compensation, with maximum freedom of movement and minimal impedance, some designs are more useful then others. In this section, the requirements are explained and design implications discussed.

### A. Scalable and independent compensation

Ideally, the amount of gravity compensation of a dedicated gravity compensation device is varied steplessly from no to full compensation of the weight of the supported limb, but is independent of the arm orientation. Early in the rehabilitation process, more compensation facilitates the use of the arm, possibly with increased cortical reorganization. By later reducing the compensation, the subjects relearn to maintain their arm posture against gravity. Secondly, with scalable compensation, transitory effects can be examined. Sukal et al. [3], for instance, gradually increased the required shoulder elevation torques by reducing the gravity compensation, and studied the effects on the achievable work area. Independent control of compensation for the upper and lower arm tailors the torque relief for shoulder and elbow and allows some control over the remaining vertical load on the shoulder.

The need for scalable compensation excludes horizontal two-dimensional systems as used in the MIT-Manus and similar systems. These systems feel like sliding over a smooth, flat, horizontal surface. They have arm rests with a fixed vertical position and are either there for the arm to rest on, or not; the amount of compensation force cannot be scaled. For independent control of compensation on the upper and lower arm, a single three-dimensional end-point controller is not sufficient. Finally, springs connected directly to sling systems result in non-linear deflection-dependent compensation and unwanted oscillations. However, spring mechanisms exist which generate deflection-independent constant forces [14].

### B. Maximum freedom of movement

In current stroke rehabilitation, many therapist ask the patients to perform functional movements, mimicking activities

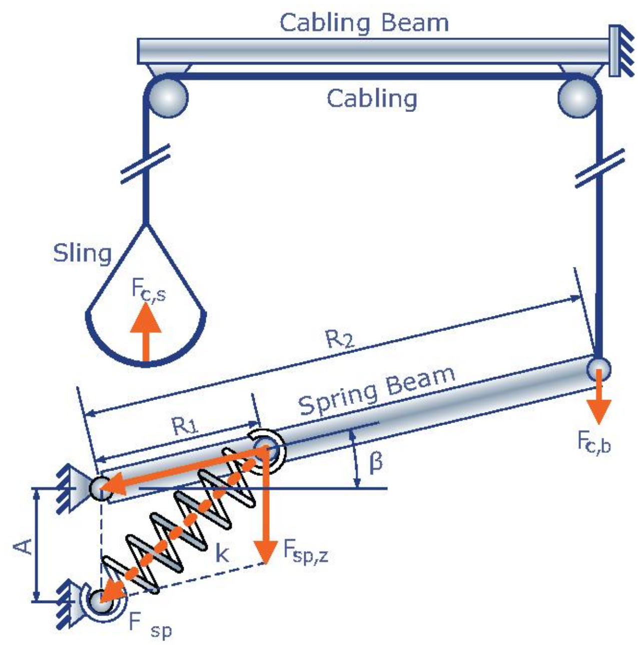


Fig. 2. Gravity compensation mechanism of which the Freebal has two, operating independently of each other and connected to the wrist and elbow. The gravity compensation force $F_{c,b}$ at the end of the beam is independent of the spring-beam angle $\beta$, even for large angles, because the decompositioned ideal spring force $F_{sp}$ in the z-direction ($F_{sp,z}$) is always equal to distance A times spring-stiffness $k$. As $F_{c,b} = F_{sp,z} * R_1/R_2$, the amount of gravity compensation can be altered by changing the spring-attachment distance $R_1$. The gravity compensation force on the sling, $F_{c,s}$, is equal to $F_{c,b}$, except for some slight (roughly +/- 10% theoretical) non-linearities at the edges of a working volume of 1 $m^3$.).

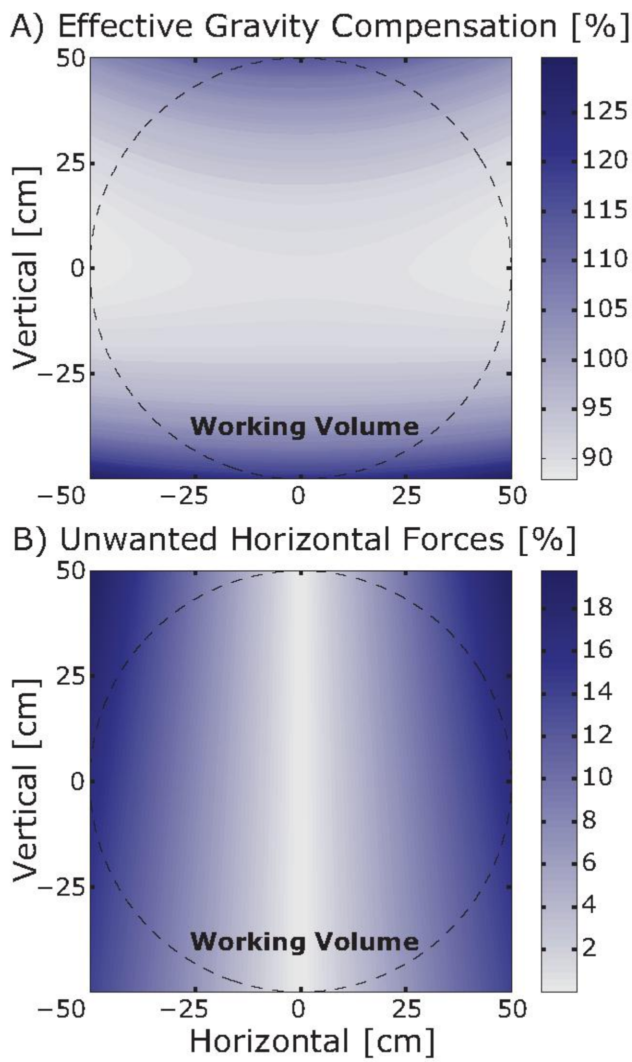


Fig. 3. Vertical cross-sectional image of the non-linearities in the working volume, resulting from the angled vertical cables. The working volume is a 1 $m$ diameter ball, centered at 1 $m$ above ground level and exactly below the foremost top cable pulley, which is at 3.5 $m$ above ground level. In the top figure, the actual amount of gravity compensation is given, and in the bottom figure, the amount of horizontal forces pulling the sling to the central vertical axis, both as percentage of the requested vertical compensation.

of daily living. For such a wide variety of movements, it is essential to have little to no restriction on the possible range of motion. Again, by providing gravity compensation with maximum freedom of movement in the early stages of rehabilitation, the rehabilitation process may be aided.

All three groups of device designs described earlier can achieve maximum freedom of movement, with some complications. A single end-point system connected to the hand does not support the entire arm, as the elbow will hang downwards. The end-point connected to the lower arm can balance the entire arm [15], but needs a connection with three rotational degrees of freedom, or else it forces the lower arm into device-dependent orientation patterns. For exoskeletons, maximum range of motion for the complicated joints of shoulder and elbow require more complex mechanisms [16]. Adding simple mechanical gravity compensation to these, requires a trade off between the weight and the side effects of the compensation system. For both end-point as sling systems, the mechanisms should be positioned such as to not limit the achievable range of motion.

### C. Minimal impedance

The limited capabilities of severely affected stroke patients should not be impeded futher by obstructing forces like inertia and friction. These forces slow the acceleration and deceleration of motions, possibly resulting in reduced movements and increased the reaction forces in the shoulder, which may lead to shoulder pains.

Here, exoskeletons and mechanical end-point systems introduce additional inertia and friction, although the experienced inertia can be reduced by active mechatronic admittance controllers, resulting in more complicated systems. Classic balancing masses connected via cables and slings to the arm also increase the inertia, and make the entire device unnecessarily heavy.

### D. Overall implications

Together, the requirement for scalable compensation independently for upper and lower arm, and maximum freedom of movement with minimal impedance in a simple, mechanical device, lead us to choose a sling support system with two ideal-spring mechanisms.

## III. Design

After evaluating several concepts, we created the Freebal (derived from Balanced Freedom and see Fig. 1). It uses two independent ideal-spring mechanisms for the compensation forces for the elbow and wrist, connected via overhanging cabling to the slings in which the arm rests. The compensation forces are scaled steplessly by changing the spring attachment points. The sling construction only restricts the lower-arm from obtaining a straight upright orientation due to sliding slings, but has full freedom of movement otherwise. The ideal-spring mechanism has almost no impedance and is simple to realize, adapt and maintain.

Using an ideal-spring mechanism [14] (see Fig. 2), it is possible to generate the constant vertical forces independent of the vertical position. This has an advantage over using complex mechatronic systems, which would include several actuators, force-sensors and controllers, but would be extremely costly [17].

The construction is made of aluminum, thus light and easy to move. The overhead beam can be lowered to below 2 $m$ for storage or movement. The device has a setup time of lower than a minute to get a subject started with exercising with the right amount of compensation. The hand of the connected arm can still grab objects in functional exercises, and the therapist has full access to the arm to guide the movement.

### A. Ideal spring mechanism

The balancing forces come from two independent ideal spring mechanisms at the base of the Freebal (see Fig. 2). The mechanisms give a constant vertical force at the endpoint of the beam. By changing the attachment point of the ideal spring on the spring beam, the vertical endpoint force can be altered. The needed amount of gravity compensation is dependent on the measured weight of the arm. By locking the spring beams and weighing the load on the two cables with simple scales, the weight can be determined. The worm-wheel slider in the spring beam can alter the spring attachment point on the beam (see Fig. 2, length $R_1$), which linearly changes the amount of compensation. The amount is indicated on the spring beam.

Spring selection influences the resolution and range of the compensation force. A stiffer spring increases the force change per revolution of the worm-wheel, and increases both the minimum and maximum compensation force. With springs with stiffnesses of 6 $kN/m$, the minimum and maximum compensation are 150 $gr$ and 5 $kg$, respectively.

The construction impedance felt by the patients is dependent on the arm movement. When the arm moves in the horizontal plane, the spring beam stays almost stationary, and little to no inertia is felt. But when the arm moves vertically, the patients feel the low reflected mass of the spring beam (190 $gr$) and a possible slight resistance in the ideal-spring mechanism and pulleys. Static and dynamic friction in the mechanism will reduce the effective compensation and are therefore minimized as much as possible.

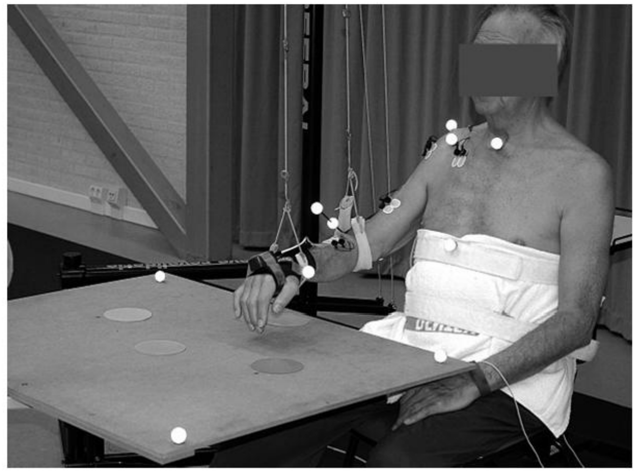

Fig. 4. Freebal is used together with both a visual tracking system and a EMG recorder. The Freebal does not obstruct the tracking of the markers, nor hinder the placement of EMG patches.

### B. Overhead cable construction

Cable pulleys on a fixed overhead cabling beam guide the cable connecting the ideal spring mechanism to the slings supports (see Fig. 1). By positioning the overhead beam up to 3.5 $m$ above ground level, the non-linearities of the angled vertical cables to the spring beam and the slings are minimized. This results in overall theoretical non-linearities of +/- 10% of the required compensation force in a working volume of a 1 $m$ diameter ball (see Fig. 3), and keeps the occurring horizontal forces below 20% of the compensation force.

Again, friction reduces the effective compensation and is minimized by careful selection of sail-boat pulleys and cabling. The small pulleys are modified by replacing their bearings with needle bearings. Inexpensive, highly flexible (though not very stiff), 3 $mm$ diameter cabling has almost no resistance around the pulleys. The lack of stiffness in the cable is no problem when connecting the sling with constant force and low friction to a low inertia mechanical systems like the ideal spring mechanism.

## IV. Discussion

Our device to investigate the effects of gravity compensation in rehabilitation robotics, is designed for maximal effective compensation with minimal undesirable side effects. Sling systems with ideal spring mechanisms are well suited for providing compensation forces. They have little movement impedance and the compensation can be scaled steplessly. Compared to exoskeletons or three-dimensional end-point devices, they are easier to construct and use for an equal range of motion, impedance and control over the compensation of the lower and upper arm. They require no external power, force sensors or active controllers and provide constant compensation forces over the entire range of movement. The device can be easily moved, serviced and used in arm rehabilitation with either sitting or standing subjects.

Experimentation learned subjects had a preference for attaching the two slings to the wrist and elbow, and not at the mass centers of the lower and upper arm. This seems to be partly caused by the harder, bony tissue, at the wrist and elbow, which stop the slings from sliding. They might also be less sensitive connection points for the gravity compensation forces. By connecting to the wrist and elbow, the weight of the upper arm is supported both by the gravity compensation on the elbow and by a residual vertical force on the shoulder.

To record the joint rotation and muscle activation, addition systems are needed. As the Freebal is mostly made from aluminum, is painted black and hardly obstructs the view on the arm, both optical as magnetic based tracking systems can be used. EMG recordings can also be done without problems. In Fig. 4, the Freebal is seen used together with both a visual tracking system and an EMG recorder [18], [19], [20], [21].

The more conventional Swedish Helparm has been reported to cause shoulder pain in patients. Although speculation, this might be caused by the Helparm only supporting the arm at the wrist and not the elbow. As most of the mass of the arm is located proximally, using the Helparm makes the shoulder bare most of the weight, but without the normal muscle forces around the shoulder keeping the humerus head stable in its shoulder socket. The arm may hang on the shoulder by passive tissue only, perhaps causing the reported pains. A recent study shows that taping the shoulder, thus assisting the passive tissue and shoulder muscles, reduces the occurrence of shoulder pain [22]. Because the Freebal also supports the arm at the elbow, the weight the shoulder carries is a lot lower. By connecting the sling to the middle of the upper arm, as discussed above, the load on the shoulder could even be completely removed.

Recently two other dedicated compensation devices were introduced; the ARMOR [15] and the T-WREX [23]. Both use ideal-spring mechanisms for scalable, vertical-position independent compensation. The ARMOR is designed as a permanent patient support for permanent attachment to a wheelchair and the T-WREX is used in stroke rehabilitation therapy. Compared to the Freebal, they don't require a high ceiling and have no horizontal forces pulling the sling to the center of the working volume. The Freebal has less inertia, a slightly larger range of motion, is easier to setup and use, while still giving the therapist full access to the limb. Compared to the ARMOR, the Freebal can scale the gravity compensation for the lower and upper arm independently, and thereby control the force on the shoulder.

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