Dampace: dynamic force-coordination trainer for the upper extremities

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***Abstract*— According to reviews, training with upper-extremities rehabilitation robotics is at least as good as regular stroke rehabilitation, probably because the robotics increase the training intensity for the patients. As an alternative to the functional approach mimicking activities of daily living, targeted force-coordination training may also have its benefits. Our passive exoskeleton, the Dampace, has controlled braking on the three rotational axes of the shoulder and one of the elbow. It is designed to combine functional training of activities of daily living with force-coordination training. The Dampace exoskeleton can assist in identifying causes behind the movement disorders of stroke patients, tackle these causes with isolated force-coordination training, possibly simultaneously over multiple joints, and then integrate the isolated training back into a functional, task-specific training protocol.**

Not needing to align the Dampace axes to the human shoulder and elbow axes overcome some of the difficulties traditionally associated with exoskeletons. Although it adds more complexity, the reduction of setup times to a few minutes and the absence of static reaction forces in the human joints, are major advantages and have been well received by therapists and physicians. Controlled braking instead of actively assisting actuators, has the advantage of inherent safety and always actively participating patients, at the cost of not being able to assist movements or create all virtual environments.

I. INTRODUCTION

Patient-friendly robotics for upper-extremities rehabilitation are used as diagnostic and therapeutic aids for a wide range of disabilities. After a stroke, improving limited arm function is an important aspect to regain functional abilities. Current robotic devices try to accomplish this by a number of different rehabilitation theories. For example, the MIT-Manus [1] assists arm movements during tasks execution [1], the MIME [2] mirrors the movement of the unaffected to the affected arm, the ACT^{3D} [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 supply 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

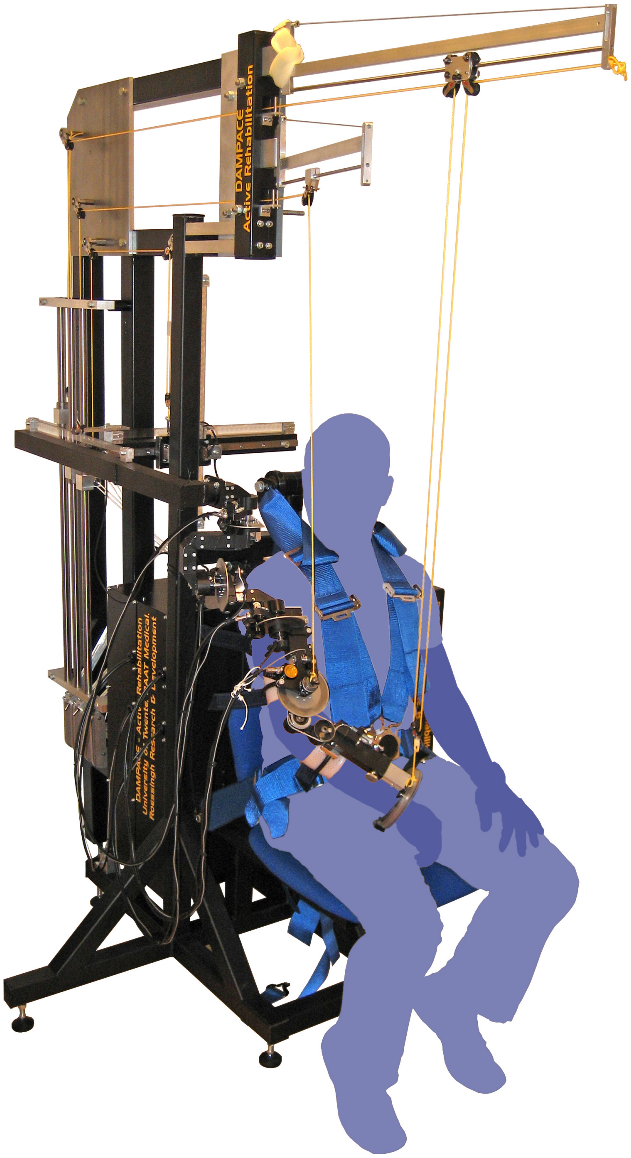

Fig. 1. Dampace: dynamic force-coordination trainer. Powered hydraulic disk brakes on the rotational axes of the shoulder and elbow can apply controlled resistance torques. Additional translating degrees of freedom at the shoulder and elbow mean the exoskeleton axes do not need to be aligned to the human axes, and allow full linear freedom of movement of the shoulder. The disk brakes cannot add energy into the system, making it, in terms of control engineering, 'passive' and inherently safe, at the cost of not being able to assist movement.

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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 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. But consistent influence on the functional abilities of the patients was not found. These three systematic reviews agree with the main principle of motor learning; the improvement in motor-control performance is directly linked with the amount of practice done [8]. However, improved motor control is not the same as increased functional ability.

The systematic reviews on the results of robotic therapies are in line with research on non-robotic upper-extremity therapy. These indicate that intensive and task-specific exercises, consisting of active, repetitive movements, give the best results [9], [10], [11]. This is because active generating movements requires more brain activity and results in better motor learning over externally-powered arm movements without active patient participation [12]. For severely affected stroke patients, active participation can be facilitated by reducing the gravitational pull on the arm, as we found in previous studies [13], [14], [15], [16].

As an alternative to the strict functional and task-specific approach, Dewald and colleagues are using non-functional movements to achieve improved motor control in stroke rehabilitation [17], [18], [19], [3]. Their multi-degree-of-freedom force-coordination training tackles a commonly identified cause of stroke patients' movement disorders; the abnormal coupling between elbow and shoulder joint torques.

Other non-functional training with support in literature are progressive resistance strength training and force-coordination training [20], [21], [22], [23], [24], [25], [26], [27], although the evidence is not conclusive [28]. The more recent combination of functional exercises with dynamic high intensity resistance training looks promising [29]. Additionally, training by actively resisting the patients' movements may also stimulate them to generate more appropriate movement patterns when emphasizing the movement error [30], [31]. General motor learning theories on which these theories are partly based, are thought to be useful for motor recovery after stroke [32], [33], [34].

Taking all approaches together, we required a training device which could help identify causes behind the movement disorders of stroke patients, tackle these causes with isolated force-coordination training, possibly over multiple joints, and then could integrate the isolated training into a functional, task-specific training protocol. In the training stages, active patient participation is essential, and by varying the levels of difficulty or using gaming or virtual reality interfaces, patients should stay challenged and motivated. This paper describes the development and evaluation of our dynamic force-coordination trainer for the upper extremities, the Dampace.

TABLE I

REQUIRED RANGE OF MOTION AND MAXIMUM RESISTANCE TORQUES FOR SHOULDER AND ELBOW, NAMED AND DEFINED ACCORDING TO ISB RECOMMENDATIONS [35] FOR RESP. THORACOHUMERAL AND HUMEROULNAR JOINT.

Joint Axis	Range of Motion [deg]	Resistance Torques [Nm]
Thoracohumeral plane of elevation	0-135	25
Thoracohumeral negative elevation	0-120	25
Thoracohumeral axial rotation	0-160	25
Humeroulnar rotation	0-135	50

II. REQUIREMENTS AND IMPLICATIONS

The principle design choice for an upper-extremity rehabilitation robotic trainer is between using end-point control (like MIT-Manus) or an exoskeleton type of orthosis (like ARMin). Secondly, if it is not needed to actively assist movements, controlled resistance could suffice. The consequences of these choices will be illuminated in this section by discussing them in relation to the device requirements. Many of these requirements were refined with the help of a select group of physicians, therapists and researchers in the Netherlands.

A. Movement assistance

Most of the current rehabilitation robotics are actively powered and designed to (partially) assist arm movements. However, when comparing training of unassisted reaching to reaching assisted by a robotic device, equal gains in range of motion were found [36]. This, and the emphasis the systematic reviews put on the active contribution of patients and levels of patients intensity as discussed above, may indicate that for motor relearning, assisting movements by robotics has little benefit over training with unassisted movement for patients with some voluntary movements. Secondly, force-coordination and error-enhanced training can be realized by controlled resistance around joint axes. Movement execution for severely affected patients, with or without minimal additional joint resistance, may be facilitated by adding the possibility of gravity compensation to the device [19], [3], [13], [14], [16], [15]. At a minimum, the weight of the device itself should not be felt by the patient.

Applying controlled resistance only, more commonly known as braking, has the advantage of being inherently safe and light weight in implementation. As a downside, actively assisting movements is impossible and virtual environments are restricted to those which do not need energy being put into the system. It will also require a separate mechanism to compensate the gravity forces on the device and limb. But as the torques needed to compensate for these forces can easily exceed 10 Nm around the shoulder axes, even an

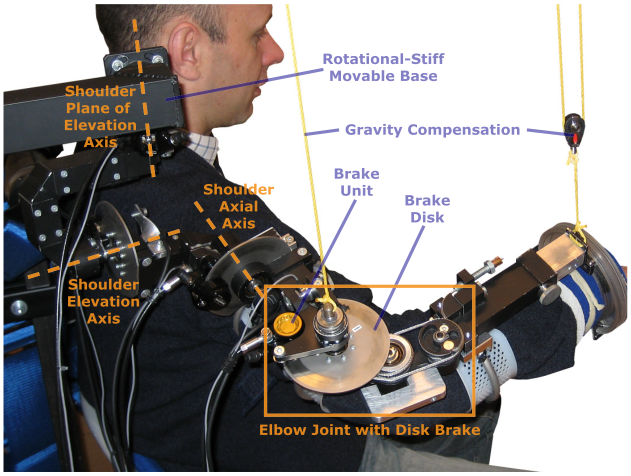

Fig. 2. Shoulder and elbow axes of the Dampace. The three shoulder axes run parallel to the plane of elevation, elevation and axial axis of Tab. I. These axes do not necessarily run through the glenohumeral rotation center, but the movable, rotational-stiff base, prevents the occurrence of shoulder reaction forces (see Fig. 3). The brake disk and brake unit are indicated too (see Fig. 4).

actively powered device may need the separate compensation mechanism. Both end-point mechanisms and exoskeletons can be fitted with brakes, actuators, and integrated gravity compensation.

B. *Control and range of motion*

To exercise most functional activities of daily living, we defined the required range of motion for the shoulder and elbow joint according to Tab. I. For object grasping movements, the shoulder and elbow angles are not only dependent on the position of the object, but also on the type of object. For instance, the arm may approach a cup of water differently from a smaller object like a pencil laying on a table at the same spot. The shoulder joint does not only have the three rotational degrees of freedom, it also has two translational degrees. Finally, humans have voluntary control over the shoulder position, but shoulder elevation rotation is also coupled with vertical shoulder translation.

By logic, a single three-dimensional end-point device is not able to independently control all four axis of shoulder and elbow simultaneously, unless at least one additional rotational degree of freedom at the end point is also controlled. Only when restricting some movement, for instance the orientation of the lower arm to the horizontal plane, can both the position of the hand and the elbow be controlled. Exoskeletons do have full independent control of all four axes of the joints, and can apply pure torques on the joint axes. Current end-point controllers mostly apply forces on the hand, resulting in possibly-painful reaction forces in the joints. On the other hand, by having no axis to align with the human, end-point controllers are less sensitive to (in)voluntary translation of the shoulder. Exoskeletons will need to be able to translate their shoulder rotation axes to get full shoulder-elevation freedom of rotation.

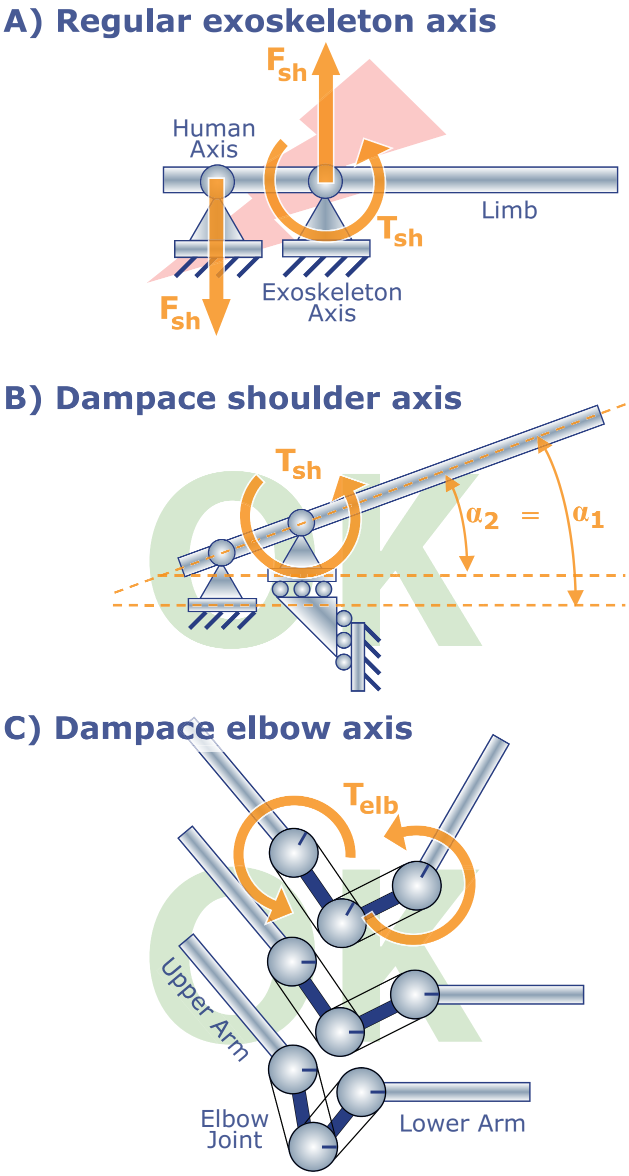

Fig. 3. Axes alignment in exoskeletons. In the top figure (A), the effects of misalignment of a axes of a regular exoskeleton and a human joint are displayed in a 2D representation, valid for both the shoulder and elbow joints. The misaligned axes work as crowbar, and rotation is only possible by deforming the soft human tissue. To prevent his, the axes need to be perfectly aligned, which requires long setup times. In the middle figure (B), a translating shoulder axis of the Dampace prevents the occurrence of the 'crowbar' reaction force. Torques can be applied to the limb off the linear-movable but rotational-stiff base. The effects are the same in 3D, although adding the two other rotational axes requires only one additional linear axis. In the bottom picture (C), the Dampace elbow joint has two extra beams near the human elbow joint, on top of which a parallelogram of cables and drums pass the lower-arm orientation to the upper arm. Translation of the joint is now independent of rotation, and vice verse, removing the requirement for elbow alignment. At the upper arm, the rotation can be controlled and measured; a torque applied here runs through the cables and drum mechanism and is applied to the lower arm, without causing reaction forces in the elbow.

C. Usability in therapy

For the device to be useful in therapy, some usability issues need to be addressed. The device has to be safe, comfortable and easy to use and set up. An appealing design will help with patient acceptability and patient motivation is enhanced by providing stimulating training environments.

Optimal, because inherent, safety is gained by having controlled resistance instead of active assistance. Comfortable use is either gained by having lower levels of actuation or resistance for an end-point system, or using an aligned exoskeleton to apply pure torques without reaction forces around the joint axes. For most of the current devices, the end-point controllers are easier in use compared to the exoskeletons, due to the longer setup times of the latter. Exoskeletons exist which do not require their axes to be aligned to the human axes [37]. This minimizes the difference in setup times and reduces some unwanted reaction forces in human joints. Both good design and stimulating gaming environments can be created with end-point controllers and exoskeletons.

D. Overall implications

Together, the requirements for movement assistance, control and range of motion, and usability in therapy for a dynamic force-coordination trainer, lead us to an auto-aligning exoskeleton with controlled resistance around the joint axis, and a separate gravity compensation system. Recorded joint torques and rotations should be usable for feedback control.

III. DESIGN

After evaluating several concepts, we created the Dampace (derived from Damped Space or Pace and see Fig. 1). The rotations of the three joints axes of the shoulder and the one of the elbow can be actively resisted by powering the hydraulic disk brakes. The exoskeleton joints do not need to be aligned to the human joints, and allows full linear freedom of movement of the shoulder for up to 15 cm in any direction. The resistance is applied as pure torques, reducing reaction forces in the shoulder and elbow joint. The weight of the exoskeleton is compensated by an overhanging cabling system connected to an ideal-spring mechanism. And feedback can be generated with any combination of the measurements of joint rotations and torques.

A. Joint alignment

In most other exoskeletons, good exoskeleton and arm axes alignment is a necessity and can be time-consuming to achieve. The Dampace overcomes this by requiring no alignment of the shoulder and elbow axes (see Fig. 2 and Fig. 3). Misaligned axes in regular exoskeletons work as crowbar, and rotation is only possible by deforming the soft human tissue. In the Dampace, the exoskeleton is connected to the main frame via a translating base, which can move freely in 3D. As the base is rotational stiff, shoulder-joint torques can be imparted off the base onto the human limb. But the torques do not generate the reaction forces seen in other exoskeletons, as when such a force occurs, the base simply translates until the force is gone. Impedance forces due to inertia of the exoskeleton and friction of the base will cause some reaction forces, but these are generally much lower than the 'crowbar' forces, especially for low-speed movements. The joint reaction forces caused by muscle activation in the musculoskeletal system inside the arm are, of course, still present.

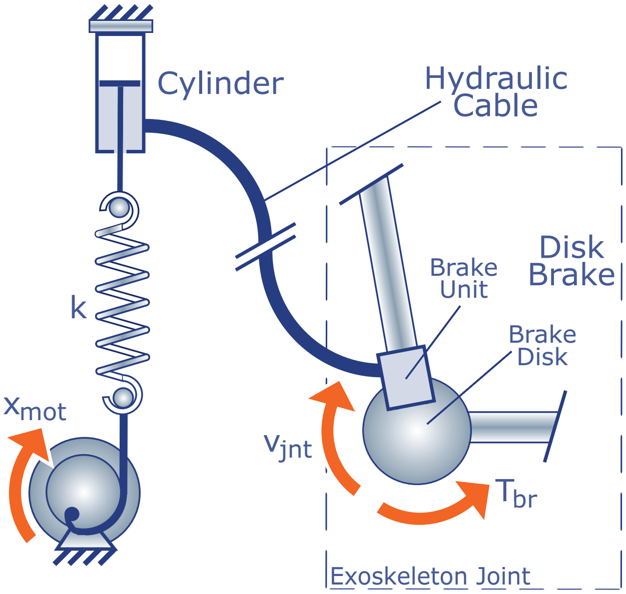

Fig. 4. Disk brake on the human joint, powered by a series elastic actuator in the base of the Dampace. The rotation of the motor x_{mot} is converted by the spring with stiffness k and the cylinder to a pressure in the hydraulic cable. This pressure is used to control the braking torque T_{br} on the exoskeleton joint. Note that the braking torque is always in the opposite direction of the joint velocity v_{jnt}.

The Dampace elbow joint has two additional beams near the human elbow axis, on top of which a parallelogram of cables and drums pass the lower-arm orientation to the upper-arm. Translation of the joint is now independent of rotation, and vice verse, removing the requirement for elbow alignment. At the upper arm, the rotation can be measured and controlled, for instance by an active actuator or brake.

B. Hydraulic disk brakes

The energy-dissipating resistance torques are possible via pneumatic, hydraulic, (electro)magnetic and mechanical constructions. Commercially available hydraulic disk brakes, however, have a very high braking torque to weight and size ratio. Via controlling the brake pressure via electric motors in a series elastic configuration [38], [39], the amount of resistance is regulated (see Fig. 4). The brakes themselves can handle up to 200 Nm and with a small-force bandwidth of up to 25 Hz. However, the dynamics of the chosen electric motors limit the actually braking force on the exoskeleton joints to 50 Nm with a bandwidth of up to 10 Hz.

In experiments with a constant brake pressure in a disk brake, varying the joint velocity from almost zero to the maximum arm velocity caused at most 10% variation on the braking torque. Because the braking torque is thus almost fully hydraulic-pressure dependent and joint-speed independent, achieving a constant braking torque requires little effort. Damping (speed-dependent resistance) was tested as well. For low torques, the results were promising, but controlling the damping with higher levels of applied torques requires better actuator dynamics and a higher maximum torque of the electric motors.

C. Gravity compensation

The gravity compensation forces come from three independent ideal-spring mechanisms at the base of the Dampace (see Fig. 5). The mechanisms give a constant vertical force at the endpoint of the spring beam, which is connected via a cabling system to the base of the exoskeleton, the elbow and the wrist. The needed amount of gravity compensation is dependent of the measured weight of the arm. By locking the shoulder elevation and elbow axis (with a horizontal elbow axis orientation) and weighing the torques around these joints, the weight of the arm can be determined. The worm-wheel slider in the spring beam can alter the spring attachment point on the beam (see Fig. 5, length R_1), which linearly changes the compensation force. The amount is indicated on the spring beam. The cable beam is vertically hinged roughly above the human shoulder, which, together with the small slider underneath the cable beam positions the gravity compensation exactly over the wrist and elbow. To reduce horizontal oscillations, a small damper was added to the cabling beam hinge.

D. Computer control

A feedback controller in the Dampace analyzes the measured rotation angles and joint torques of the four axes and applies resistance torque to the joints based on these measurements. The controllers are programmed in Matlab Simulink (http://www.mathworks.com) and compiled to run in an open-source, real-time Linux environment (RTAI, http://www.rtai.org) with open-source hardware drivers (COMEDI, http://www.comedi.org) for the National Instruments DAQ devices (http://www.ni.com), and have real-time logging and graphical user interface possibilities. The controller runs at a minimum of 1000 Hz on a single core Intel Pentium IV computer.

E. Identification, isolation, integration

In the full set of identifying the limitations of a specific stroke patients, isolating the problem and combating these with functional or targeted force-coordination exercises, and then integrating the achieved improvement back into activities of daily living, the Dampace can make an important contribution. Identification can be helped by determining the active, unrestricted range of motion, the maximum isometric and resisted forces and speeds, or any other combination of active forces and movements, all measured directly in joint space. In functional or targeted force-coordination exercises, the controller can apply resistance to specific parts of the movement. This can both restrict or guide the arm to stay inside a desired movement space, or make a movement harder to do, thereby increasing the training intensity. Finally, at the end of the rehabilitation process, the isolated and targeted training exercises can be gradually integrated into fully functional movements. Thus a force-coordination training to increase the arm strength and control of, for example, an extended arm can be turned into manipulating real objects in a kitchen type of environment. In all stages, the hand can be an integral part of the exercises, as it is always unrestricted and left free.

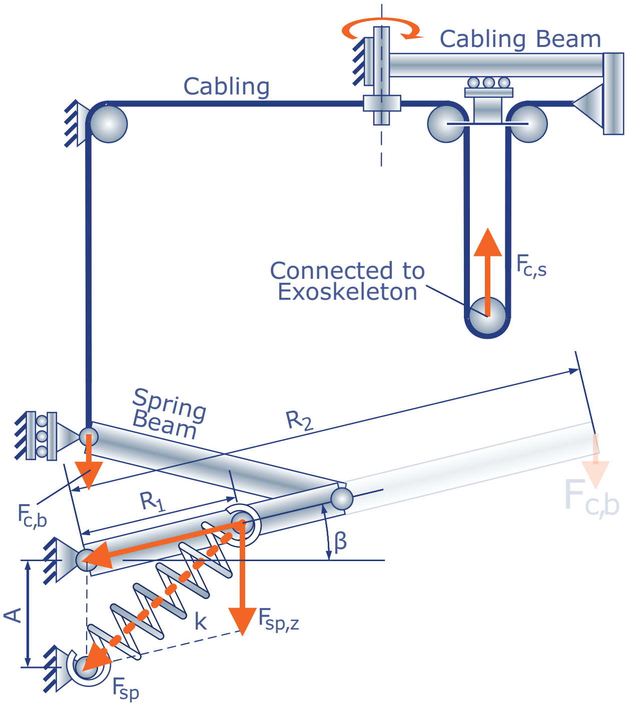

Fig. 5. Gravity compensation mechanism, of which the Dampace has three, operating independently of each other and connected to the exoskeleton base, the elbow and the wrist. The gravity compensation force $F_{c,b}$ at the end of the split spring beam is independent of the spring-beam angle β for all 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 here equal to $2 * F_{c,b}$ in a working volume as defined by Tab. I. The cabling beam is vertically hinged roughly above the human shoulder, which, together with the small slider underneath the cabling beam, positions the gravity compensation exactly over the wrist and elbow.

Although an exoskeleton is probably not the best way to achieve perfect haptic feedback, it is possible to simulate some environments. Feeling like motion under water requires damping, while a regular resistance is needed for lifting a heavy object or moving it on a rough surface. More elaborated environments [40] with time-, position-, and directional-dependent resistance and damping have less clear real-world synonyms, but could be interesting for studying specific symptoms. Even so, the environments which can be simulated are limited to those which require no energy input to any part of the system, as the resistance trainer can only disperse energy and the applied torques are always working against the rotational direction. Another restriction

Fig. 6. Integrated gaming environment connected to Dampace torques and movements. Either isometric thoracohumeral-elevation torques or isotone rotations are mapped to the gas paddle in the racing game, and either humeroulnar isometric torques or isotone rotations to the steering wheel. Good coordination of simultaneous shoulder and elbow torques is thus required for good driving control in the game and should motivate the subjects to keep exercising.

is the limited bandwidth of the brakes (10 Hz), which make it impossible to create hard surfaces. But these are probably not needed for rehabilitation training. With all these environments, it should be realised that the haptic feedback is passed on from the exoskeleton to the human arm via cuffs to the upper and lower arm, and not via the hand; although the decomposition of hand forces to shoulder and elbow torques might be correct, the 'erroneous' tactile connections do influence the haptic sensation.

In another current example, specific training combats the effects of unwanted multi-joint muscle synergies [18], which is important for patients to regain more functional use in their affected side. To motivate subjects, the human movement and force execution are linked to a gaming console (see Fig.6). Either isometric thoracohumeral-elevation torques or isotone rotations are mapped to the gas paddle in the racing game, and either humeroulnar isometric torques or isotone rotations to the steering wheel. Good coordination of simultaneous shoulder and elbow torques is thus required for good driving control in the game and should motivate the subjects to keep exercising. Although this specific game is probably to demanding for elderly stroke patients, it gives an impression of alternative possibilities.

IV. DISCUSSION

To combine functional training of activities of daily living with force-coordination training, the Dampace is designed to be used for assisting in identifying causes behind the movement disorders of stroke patients, tackling these causes with isolated force-coordination training, possible over multiple joints, and then integrating the isolated training back into functional, task-specific training protocols.

Not needing to align the Dampace axes to the human shoulder and elbow axes overcomes some of the difficulties traditionally associated with exoskeletons. Although it adds more complexity, the reduction of setup times to a few minutes and the absence of most reaction forces in the human joints, is a major advantages and has been well received by therapists and physicians. Controlled braking instead of actively assisting actuators, has the advantage of inherent safety and always actively participating patients, at the cost of not being able to assist movements or create some virtual environments. The inherent safety is an important aspect to ensure confidence in the device by patients, therapists and ethical commissions alike.

Although actively controlled resistance may be enough for motor relearning after a stroke, preliminary results of other, active robotics seems to indicate that properly supplied assistance can help recovery times. Determining the proper kind of assistance is thus still a matter of current research in motor skill training and adaptive shared control contexts.

Early experiments with healthy subjects and a couple of stroke subjects showed that the attention paid to the aligning of the axis and the friction control in the translating exoskeleton base and gravity compensation was well spend. Yet, for precise following of the joint angles, better arm cuffs are needed, possibly using bony landmarks, as some subjects had very slack arm tissue. This caused the exoskeleton to have angle offsets to the the limb when subjected to torques above 25 Nm. Finally, with another setup we determined that up to 120 Nm of static braking force may be needed for isometric measurements with healthy subjects, which is currently far beyond the Dampace capabilities.

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