Effects of Gravity Compensation on the Range-of-Motion of the Upper Extremities in Robotic Rehabilitation after Stroke

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Abstract

Gravity compensation has an effect on the movement executions of the upper extemities of stroke patients. Our basic gravity compensation system increased the range-of-motion work area of patients with below average Fugl-Meyer scores. Similarly, the horizontal shoulder-wrist linear stretching distance also increases.

Introduction

Stroke is the leading cause of disabilities in Western civilisations. In the last decade, several therapeutic devices have been developed by research groups from around the world. These have made rehabilitation therapy less labour intensive and more challenging for the patient, and provided better measurements for the therapists and scientific community.

Recently, a systematically review from our project group on literature assessing the effect of robot-aided therapy on stroke patients' upper-limb motor control and functional abilities [4], concluded that robot-aided therapy of the proximal upper limb improves short- and long-term motor control of the paretic shoulder and elbow in sub-acute and chronic patients, although without consistent influence on functional abilities. In addition, robot-aided therapy appears to improve motor control more than conventional therapy.

Most of the current upper-extremity robotic devices use some form of gravity compensation. For instance, ITM's InMotion Shoulder-Elbow Robot (previously known as the MIT-MANUS [2]) has the lower arm supported by a stiff connection to the device-hand interface. The GENTLE/s [3] connects the wrist to a haptic device, while the arm is hung in two supporting gravity compensation slings. And at the Rehabilitation Institute of Chicago, they have used slides on an air table [1] and a haptic device [5] to support the arm in their studies of the effects of synergetic joint-torque couplings in stroke patients.

The gravity compensation or support of these and other robotic devices basically are either stiff limiters of the vertical arm movement [2, 1], or mechanisms which apply upward-directed forces on an otherwise free-moving arm [3, 5]. Both of these types reduce the required anti-gravity joint torques, but a stiff limiter also restricts the movement to the horizontal plane. For example, a patient with movement control deficits makes stabilised horizontal movement even if he also uses muscles which would normally move the arm out of the horizontal plane. Therefore, a stiff vertical-limiting gravity support may give higher, but not necessarily better, results in the horizontal plane [5].

Gravity compensation in stroke rehabilitation could be useful tool on its own. Severely affected patients can be given functional limb-coordination therapy at an earlier stage because they don't need to utilise all their remaining strength for lifting their arm. And the effects of synergetic joint-torque couplings may be temporarily reduced [5], facilitating better movement executions during therapy.

To assist further developments in rehabilitation robotics, we have investigated what the effect is of using gravity

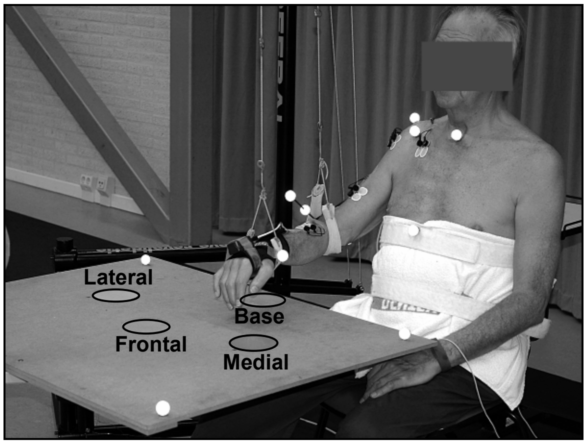

Figure 2: A subject strapped to the chair with the black Freebal gravity compensation system just behind the table. The two slings of the Freebal are connected to the wrist and elbow (see Figure 1).

compensation on the movement execution of stroke patients. In this paper, we will report on the results achieved in linear stretch and circular range-of-motion (ROM) trails.

Methods

In this cross-sectional study, the results of ten healthy subjects are compared to nine stroke patients, all with informed consent.

The patients were recruited at the local rehabilitation centre with inclusion criteria: acute or chronic; dorsal flexion of at least 20 degrees in wrist and 10 degrees in fingers. The exclusion criteria were: additional orthopaedic diseases of either of the upper extremities; shoulder pain; severe impairment of cognition and communication; psychiatric co-morbidity.

The mean (and standard deviation) age of the patients was 60.1 (14.2) years, and 65.9 (6.4) for healthy subjects. The patients' time post first stroke was 7.7 (13.2) months and Fugl-Meyer (FM) upper-extremity score 43.0 (8.6) out of 66. The patients used their affected and the healthy subjects their dominant arm.

The movements were recorded with a Vicon position-tracking system, with the optical markers positioned on the arm and trunk according to the ISB recommendations [6].

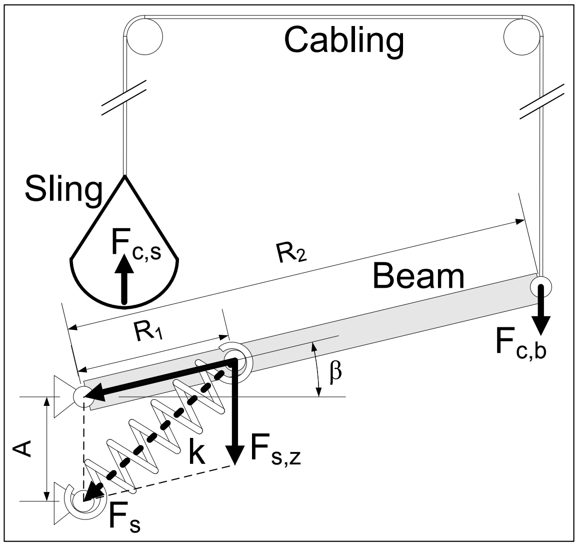

Figure 1: Gravity compensation mechanism of which the Freebal has two, operating independently of each other. The gravity compensation force $F_{c,b}$ at the end of the beam is independent of the beam angle β because the decompositioned ideal spring force F_s in the z-direction ($F_{s,z}$) is always equal to distance A times spring-stiffness k. $F_{c,b} = F_{s,y} * R_1/R_2$, thus by changing the spring-attachment distance R_1, the amount of gravity compensation can be altered. The gravity compensation force on the sling $F_{c,s}$ is equal to $F_{c,b}$ except for some slight non-linearities due to the cabling system (roughly +/- 10% at the edges of a working volume of $1m^3$).

Gravity support was provided by our Freebal gravity compensation system, which generates the compensation force with an inertia-free ideal-spring mechanism (see Figure 1). The wrist and elbow of the subjects were hung in the two slings of the Freebal (see Figure 2). The amount of gravity compensation was set to either zero or the exact measured weight of the arm.

Three coloured target dots and a base dot were placed on the table, which was positioned as low as possible just above the legs, with the base dot exactly underneath

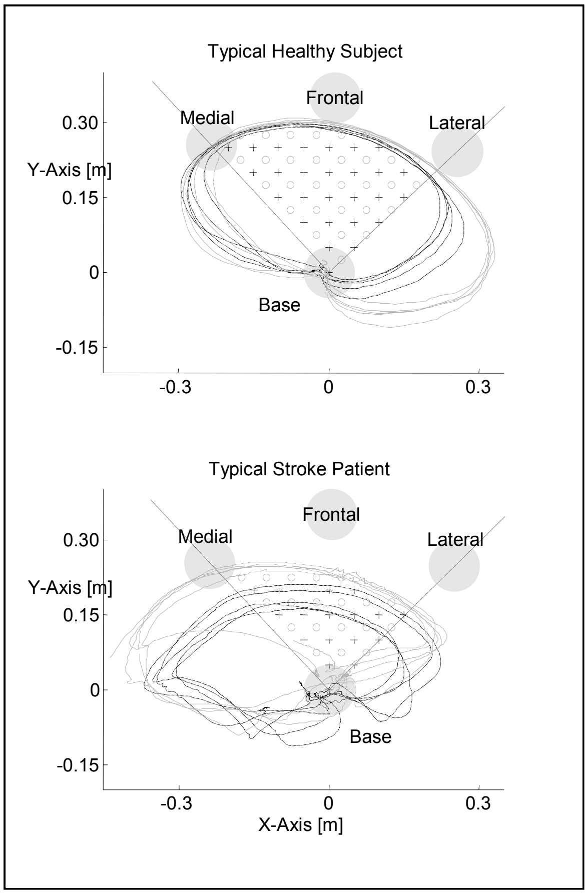

Figure 3: Typical examples of wrist paths, relative to the dynamic shoulder position, in ROM trials for a typical healthy subject (top figure) and typical patient (bottom figure) Black dotted lines are without gravity compensation, grey lines with. The ROM work area is defined as the area enclosed by the medial, base and lateral dots (stripped black line) and the relative wrist paths; the black plusses mark the work area without compensation, the grey circles with. The paths are plotted with an offset which positions the wrist above the base dot at the start of the movement.

the fingertips postured with 90 degrees of elbow flexion in the sagittal plane.

The participants were randomized into two groups. The first group performed the task first with gravity compensation and then without. The second group performed the tasks vice versa.

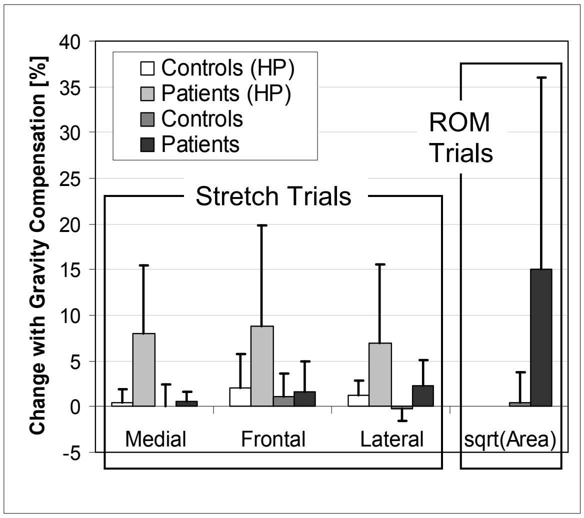

Figure 4: Changes (in %, with standard deviation) from trials without gravity compensation to trials with, for stretch and range-of-motion (ROM) trials. The results of the stretch trials (in target-dot directions) are given in changes of the maximum shoulder-wrist distance. This distance is either the horizontal projected distance (HP), or the three-dimensional distance. Results of the ROM trials are given in changes of the square-root of the work areas.

For the stretch trials, the subjects had to move their hand from the base dot as far as possible in free air in the direction of one of the three target dots, repeated five times successively for each target. The target dots were ordered from medial to lateral. Both the maximum-obtained horizontal as maximum-obtained three-dimensional (3D) shoulder-wrist distance are used as outcome measurements.

For the range-of-motion trials, the subjects had to make as large as possible roughly-circular horizontal movement in free air, starting from and ending at the base dot, repeated five times. The first set of five movements started in the medial direction of the body, the second in the lateral. Though the instructions were to make as big a ROM movement as possible, the focus of this experiment is on the results in the defined medial, frontal and lateral target-dot directions. The outcome measurement, the square root of the work area, is therefore limited to the area also enclosed by the medial, base and lateral target-dots.

The measurements with gravity compensation are compared to those without, and averaged for all healthy subjects or all patients.

Results

In Figure 3, two typical examples of ROM wrist paths and the resulting areas are given. The changes (in %) from without compensation to with are given in Figure 4.

Discussion

In literature [5], the increase in ROM work area recalculated according to our definition, can be as high as 300%. In that study, the patient had a FM score of 30 out of 66, compared to our mean value of 43. In our study, there seems to be a correlation between FM scores and achievable ROM work area; the strongest increase was 160% for a patient with a FM score of 36. Above FM scores of 49, no patient showed any clear ROM work area enlargement.

For the stretch trials with stroke patients, there is a difference between results of the shoulder-wrist distance in 3D-coordinates and on the horizontal projections. Without compensation, many of the patients were only able to lift there arm just above the table, which severely limited the achievable horizontal wrist-shoulder distance. With compensation, they did lift their arm higher in the air, leading to a greater horizontal shoulder-wrist distance. This is logical as the humerus elevation-torque requirement increases with the humerus elevation angle.

Conclusions

The results show that even with a simple gravity compensation system, the ROM work area can be enlarged, even if this is limited to patients with lower FM scores. Similarly, the results of the linear stretch trials show an increase in the horizontal shoulder-wrist distance, which is mostly explained by the patients being able to lift their arm higher against gravity.

Acknowledgements

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References

[1] RF Beer, JPA Dewald, ML Dawson, and WZ Rymer. Target-dependent differences between free and constrained arm movements in chronic hemiparesis. *Exp Brain Res*, 156(4):458–70, Jun 2004.

[2] N Hogan, HI Krebs, A Sharon, and J Charnnarong. Interactive robotic therapist. Patent, Nov 1995. US 5,466,213.

[3] R Loureiro, F Amirabdollahian, S Coote, E Stokes, and WS Harwin. Using haptics technology to deliver motivational therapies in stroke patients: Concepts and initial pilot studies. unpublished, 2001.

[4] GB Prange, MJA Jannink, CGM Groothuis-Oudshoorn, HJ Hermens, and MJ IJzerman. Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. *J Rehabil Res Dev*, 43(2):171–184, 2006.

[5] T.M. Sukal, M.D. Ellis, and J.P.A. Dewald. Dynamic characterization of upper limb discoordination following hemiparetic stroke. In *Rehabilitation Robotics, 2005. ICORR 2005. 9th International Conference on*, pages 519–521, 28 June-1 July 2005.

[6] G Wu, FCT Van der Helm, HEJ Veeger, M Makhsous, P Van Roy, C Anglin, J Nagels, AR Karduna, K McQuade, X Wang, FW Werner, and B Buchholz. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion–part II: shoulder, elbow, wrist and hand. *J Biomech*, 38(5):981–992, 2005.