Facilitating robot-assisted training in MS patients with arm paresis

A procedure to individually determine gravity compensation

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Abstract—**Gravity compensation (GC) of the arm is used to facilitate arm movements in conventional therapy as well as in robot-assisted rehabilitation of neurologically impaired persons. Positive effects of GC on Range of Motion (ROM) have been demonstrated in stroke. In Multiple Sclerosis (MS), research regarding this topic is lacking. Since an active participation of the patient is required for effective training, full support of the arm might not be advisable. The present study reports on the development of a procedure to measure actively the individual need for GC and to estimate the influence of GC on ROM during reaching, lifting and transporting in severely affected Persons with MS (PwMS). Ten PwMS were tested with the procedure for determination of GC. Maximal reaching movements were performed in a 3D space in three conditions: No support (NS), with GC by the HapticMaster (GC-HM) and with GC by the HapticMaster combined with a sling suspension system (GC-HMS). For the total sample, significant correlations were found between the amount of GC and clinical tests for upper limb function. In four subjects with severe arm dysfunction it was found that mean ROM is larger in the GC-HMS condition compared to the GC-HM condition, and in the GC-HM condition compared to the NS condition, suggesting positive effects of GC on active ROM in PwMS. Therefore, GC could have a positive effect on arm rehabilitation by enabling the PwMS to actively reach a larger ROM during training.**

Keywords-multiple sclerosis; gravity compensation; haptic robot

I. INTRODUCTION

Multiple Sclerosis (MS) is a chronic progressive disease which affects the central nervous system resulting in neuromotor disorders such as muscle weakness and spasticity and difficulties with coordination and balance. Also visual, cognitive and sensory dysfunctions are common in this group of patients [1]. As the disease progresses, the upper limbs get more affected which may lead to accumulated disability. A Swedish study found that 76% of a Swedish sample, consisting of 219 Persons with MS (PwMS), showed at least some disability regarding manual dexterity, leading to a significantly negative impact on the performance of activities of daily life in half of all patients [2].

Robotic devices are getting more and more familiar as a therapeutic medium to augment rehabilitation outcomes in neurologic disorders, such as stroke and MS, when being used as an additional therapy [3]. Reviews in stroke, using different types of robotic devices for different degrees of arm dysfunction, have demonstrated overall effects on arm motor function in both (sub)acute and chronic stroke patients [4-6]. These studies made use of different types of robots and electro-mechanical devices for the upper limb, mostly differentiated into exoskeletons and end-effectors.

Gravity compensation (GC) of the arm is often used in conventional therapy as well as in robot-assisted rehabilitation, to facilitate active training in neurologically impaired persons. The use of GC by robotic devices has already shown

beneficial effects on Range Of Motion (ROM) for reaching in persons after stroke. A pilot study of Sanchez et al. (2006) [7] demonstrated enlarged contra-lateral and vertical reaching ROM when GC was applied in 9 chronic stroke patients, while also Beer, Ellis, Holubar and Dewald (2007) [8] found an augmented ROM during horizontal reaching ROM in stroke. Reference [9] demonstrated slightly larger ROM when GC was used in functional 3-dimensional reaching movements, starting with the hand at waist height and reaching to a target at shoulder height. A possible explanation for these positive effects in stroke may be a reduction in abnormal coactivation of the elbow flexors with the shoulder abductors during GC , resulting in an increased ROM [8;10;11].

Although upper limb dysfunction in MS and stroke are both caused by central brain damage, with upper motor neuron lesion signs as muscle weakness and hypertonia, it is uncertain whether the same pathological movement patterns are present in both disorders. Therefore, one has to be careful to assume that the influence of GC on movement capacities is identical in MS compared to persons after stroke. In MS, no studies were found specifically focusing on the influence of GC on upper limb ROM but one study reported beneficial effects, in 10 severely affected PwMS, on activity level after arm training that implied GC during arm training [12]. The Armeo Spring (Hocoma AG, Volketswil, Switzerland), which is an electromechanical exoskeleton with the ability to provide GC that can be individually adapted to the subject's needs and progress, was used. However, no standard procedure by which the amount of GC was determined, is available.

The present study on GC is part of a research project (INTERREG-IV-project "Rehabilitation Robotics II" with code IVA-VLANED-1.14) that investigates the effects of arm training with a haptic robot in a 3-dimensional workspace to interact in a virtual (visual and haptic) learning environment [13]. Haptic robots, such as the Phantom and HapticMaster (HM), are typical end-effectors and can assist the movement of the patient. In our project, gravity support for the upper limb is applied with the aim to enlarge active ROM (aROM), as such enabling the patients to practice an extensive amount of active movement repetitions (training overload) which is required for improved muscle performance [14]. For this reason, a procedure was developed to determine the appropriate amount of GC that an individual patient requires, while avoiding 'oversupporting' the patient's arm. Therefore, a procedure in which GC is determined by the active motor capabilities of the patient was chosen rather than a passive method or a standard weight. This paper reports on the reliability and validity of a procedure to determine the amount of GC, provided with the HapticMaster as well as with an external sling, that was determined during an active procedure in ten persons with arm paresis due to MS. Relations with clinical characteristics as well as the effects of different levels of anti-gravity support on aROM for MS patients with severe arm paresis are documented.

II. MATERIALS AND METHODS

A. Subjects: clinical characteristics and outcome measures

Ten subjects with upper limb weakness due to Multiple Sclerosis, diagnosed according to the McDonald criteria, participated in this study (6m,4f). Mean age was 57,8 years (range 49-65). Overall disability, as rated with the Expanded Disability Status Scale (0-10), was 7,85 (range 6-8,5), were score 0 corresponds to a normal neurological examination [15]. Patients with upper limb dysfunction due to muscle weakness, as determined by the Motricity Index (score between 18 and 83), were included [16]. Exclusion was provided if an MS relapse occurred or relapse-related treatment with glucocorticosteroids was used in the last month before study onset or if the patient had manifest visual or mental problems interfering with task execution.

Upper limb strength was determined by means of the Motricity index (MI; maximal score=100). Motor function was evaluated using the arm motor section of the Brunnstrom Fugl-Meyer test (FM; maximal score =66), distinguishing a proximal (elbow and shoulder) and a distal score (wrist and hand) [17]. Upper limb functional capacity was assessed with the Action Research Arm Test (ARAT; maximal score=57) [18].

Ethical approval was obtained from the ethical committee of the Rehabilitation and MS center of Overpelt, and the Medical Ethical Committee of the University of Hasselt. All participants gave their written consent.

B. Robotic System description and gravity compensation

For this study, a 3DOF HapticMaster (HM) was used (MOOG, Amsterdam, The Netherlands). An adapted 3DOF ADL gimbal (MOOG) with a hand splint was used to connect the participant's hand to the HM, allowing relatively unconstrained wrist movements. The combination of the HM with the gimbal results in a 6DOF system.
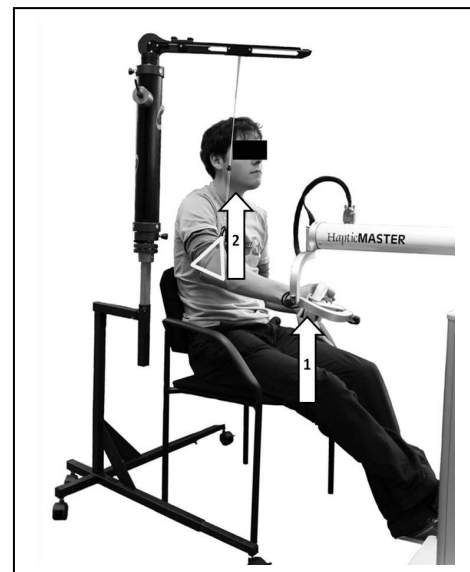

Figure 1. Set-up of HapticMaster support (1) and additional Sling support on the elbow (2)

Because the haptic device is an end-effector, only able to support the hand (see figure 1, support 1), additionally a suspension sling (FOCAL Meditech BV, Tilburg, The Netherlands) was used to provide GC at the elbow (figure 1: white triangle and support 2) if required in patients with severe arm dysfunction. The workspace of the HM was limited to 36 cm for depth, 40cm height and 1 rad for medial/lateral movements.

Bearing in mind that an active contribution of the subjects was asked during interaction in a virtual learning environment by means of training with the HM [13], an active arm procedure was developed in order to determine the appropriate amount of GC: the subject was placed on a standard chair with the robot arm of the HM in an end position towards the subject. The ADL gimbal was positioned 10 centimeters away from the body (face/torso) for safety reasons. After this, the hand of the subject was attached in a hand splint, and the patient's arm was placed in a 90° shoulder anteflexion position so that the arm reached forward with the hand, elbow and shoulder at the same height in the horizontal plane. Then, the elbow was flexed to 45° while the shoulder and hand remained in line with the arm of the HM (straight arm = 0°).

The subject was then instructed to actively keep his arm in this position during 30 seconds after the support of the therapist was removed. Hand position was visualized on a computer screen by a green ball, representing the height of the hand, that had to be kept between two horizontal lines (Figure 2). By means of visual feedback, the green color of the ball turned orange and red to indicate worsening posture. A haptic spring (not made visible on the computer screen) was implemented at which the ball was attached to. This spring
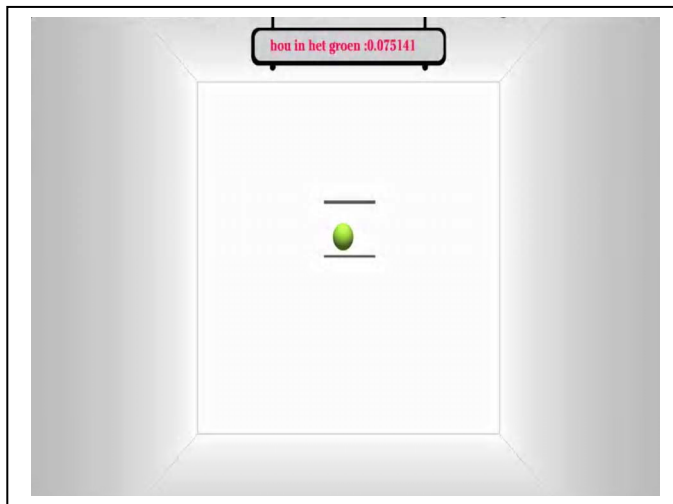

Figure 2. Determination of GC: the virtual hand position (green ball) had to be actively positioned between two horizontal lines during 30".

gave a vertical resistance when the arm was lowered below the lower horizontal line. The system measured the amount of assistive force (in Newton) that was needed to keep the arm up during the last 10 seconds of the 30" measurement. This value was stored in an underlying database to be used afterwards during the robotic evaluation and training as an GC aid.

In case of observation of compensational movements (dropping of the elbow, excessive lifting of the shoulder, contralateral movement of the torso) during this procedure, an additional suspension sling (Focal Meditech BV, Tilburg, the Netherlands) was added to support the elbow position. Anti-gravity support by the sling was added until the compensational movements disappeared. Hereafter, the entire procedure was repeated with the sling attached to measure the adapted amount of anti-gravity support with the HM.

In the abovementioned procedures, the three conditions can be deducted, namely when the GC was zero, when the GC was more than zero and when the sling was added. These three conditions were named no support (NS), gravity compensation by the HM (GC-HM) and gravity compensation by the HM with additional Sling utilization (GC-HMS).

C. Robot outcome measures

Starting position for the aROM measurement protocol was the same as for the antigravity determination, except that the height of the hand was now set midway between the shoulder and knee, while elbow flexion remained at 45° flexion. This position is different from that used in the above mentioned anti-gravity support procedure as active movements in all directions (minimal distance of 6 cm) are required rather than the maintenance of a more difficult position used to determine the needs for support. The directions were medial-lateral (transporting), forward-backward (reaching & retrieving) and upward-downward (lifting & putting down). Subjects were asked to move their arm as far as possible in these directions (expressed in cm), starting from the standardized middle position.

D. Experimental design and Statistical analysis

This study wanted to investigate the reliability and validity of a procedure to determine anti-gravity support as well as to examine the effects of different levels of anti-gravity support on the aROM in MS patients with severe arm paresis.

Repeated measurements of the GC procedure were executed to examine test-retest reliability of the procedure. Intraclass Correlation Coefficients (ICC) were calculated for all participants.

To investigate face validity of the procedure, clinical outcome measures were correlated with the amount of anti-gravity support determined with the procedure using Spearman correlation coefficients.

The Wilcoxon signed rank test was used to determine the effects of the three different levels of assistance in 4 patients with severe arm dysfunction only (NS, GC-HM, GC-HMS). Additional descriptive analyses were used given sample size.

The level of significance was set to $p < 0.05$ for all analyses.

III. RESULTS

A. Amount of gravity compensation

Table 1 presents an overview of the clinical outcome measures for the arm and the determined amount of GC (Newton) provided by the HM. For persons that needed the sling, the amount of antigravity provided by the HM while the

sling was attached to the arm is given as well as the support by the sling itself. For the latter subgroup of patients (n=4), it is observed that the amount of antigravity by the HM measured with the sling attached to the arm is smaller (mean 2.56) than the amount of antigravity measured without sling (mean 4.17), p=0.06 (Mann-Whitney U).

According to the Intraclass Correlation Coefficients, the GC measurement procedure was consistent for all participants between two repeated measurements administered in the same session (ICC=0.767).

TABLE I.   CLINICAL OUTCOME MEASURES AND VALUES FOR GC

PTS	HM (N)	Sling (kg)	HM+ SL (kg)	FMprox	FMdist	MI	ARAT
1	0,13			33	24	55	57
2	3,13	2	0,13	23	21	59	16
3	0			34	24	83	39
4	0,57			31	19	66	50
5	7,29	1,5	3,42	19	14	18	9
6	0,19			32	22	60	47
7	0,26	1,1	0	17	13	47	15
8	0,435			31	21	60	40
9	10,15	1,7	9,245	6	0	18	0
10	0	1	0	26	17	61	27

PTS: patients, HM: HapticMaster, MS+SL: HapticMaster + Sling, FMprox: Fügl-Meyer proximal score, FMdis: Fügl-Meyer distal score, BFM: Brunnstrom-Fügl-Meyer total score, MI: Motricity Index, ARAT: Action Research Arm Test

B. Amount of gravity compensation in relation to clinical tests

The determined amount of GC by the HM showed a moderate significant negative correlation with muscle strength (r = -0.64), measured by the Motricity Index. No significant correlation was found between HM support with the total score on the BFM, that focuses on upper limb motor function and movement patterns. However, a highly significant negative correlation was found with scores on the proximal part of the BFM (r = -0.70), while no correlation was found with distal hand function. The ARAT, a test in which object manipulation plays a important role, was not significantly correlated to the amount of anti-gravity support by the HM.

C. Effects of GC on active 3D ROM in patients with severe muscle weakness, requiring a sling

Table 2 presents the distances (cm) subjects could reach in three directions; forward, lateral and upward. This distance was compared between three conditions (NS, GC-HM and GC-HMS). Numbers with <6cm* indicate that this patient could not move the minimally required 6cm in that direction. Numbers marked with # indicate that movements were larger than the workspace of the HM. In these directions subjects might have been able to reach out further than the mentioned distances, but workspace properties of the system restricted their movement.

Sample sizes were too small to perform statistical analysis, therefore only descriptive statistics were used. Delta-values between the NS and the GC-HM condition, were positive or zero in all three directions for 3 out of four subjects and are positive in all but one direction (lateral) for subject 2. A positive delta-value indicates a larger ROM in the GC-HM condition compared to the NS condition. Mean delta-values amount to 4 cm in forward direction, 7 cm in lateral direction and 6 cm in upward direction.

The addition of the sling seems to give a small additional gain in aROM over HM support only. This is mainly observed in the upward direction. Three out of four subjects show a positive or zero delta-value for all three directions, whereas subject 7 shows a negative or zero delta-value in all conditions. Mean delta-values are positive and amount to 1cm for forward direction, 3 cm for lateral direction and 7 cm for upward direction. Zero delta-values were mainly caused by the minimal movement requirements that weren't reached in both conditions or by the subject movements that were restricted by the workspace of the HM in both conditions.

IV. DISCUSSION

The presented pilot study illustrates an active procedure to determine the amount of GC that is needed to optimize training by means of a haptic end-effector robot. Results indicated that GC-HM, though in general relatively small, relates well to dysfunction in muscle strength and proximal arm movements as measured by clinical tests. In a subgroup of MS patients (n=4) with severe arm dysfunction, a combined GC-HM as well as additional sling support at the elbow seemed to lead to enlarged reaching movements in three directions but further research on the optimal amount of GC is needed. It is thought that GC will allow for better training of motor function and coordination.

For the total group (n=10), it was found that the amount of GC-HM determined by the active positioning method was moderately but significantly correlated with muscle strength (MI) and highly with proximal arm movements as measured with the BFM. No correlation was found with clinical tests including hand function and object manipulation (distal part of the BFM and the ARAT).

TABLE II.   AROM DURING DIFFERENT LEVELS OF ASSISTANCE (N=4)

	NS	GS	GSS
Depth			
Subj. 2	<6*	10	13
Subj. 5	<6*	<6*	8
Subj. 7	9	20#	17
Subj. 9	<6*	<6*	<6*
Lateral			
Subj. 2	23	19	28
Subj. 5	<6*	29	32
Subj. 7	23	25	25
Subj. 9	<6*	13	14
Upward			
Subj. 2	20	23#	23#
Subj. 5	<6*	11	26
Subj. 7	14	29#	27
Subj. 9	<6*	<6*	17

Data represented in centimeters, * minimum ROM not reached, #ROM value restricted by limit HM
NS: No Support, GC-HM: Antigravity Support HapticMaster, GC-HMS: Antigravity Support HapticMaster + Sling

These findings lay in the line of expectation since the procedure for determination of GC involves mainly proximal arm muscle activation, but hardly any distal component besides forearm rotation. Rotational forces may take place at the

shoulder during this procedure but is likely reduced by using the Sling device. This way the user can focus more on the active control of the movements in the elbow and hand because less force is needed to maintain the position of the arm. The significant correlations between the amount of GC-HM and clinically tested motor function is of importance, as it provides support for the validity of our approach that determines the needs of patients based on active positioning. This procedures seems more individually adapted to one's motor capacities compared to providing GC based on standard calculations of arm weight which do not take the residual individual arm function into account. Besides, high ICC's demonstrated that the determined GC was consistent over repeated measurements.

It is well documented in stroke patients that the application of GC to the upper limb facilitates a larger reaching ROM [7-9]. Our pilot study in a group of four PwMS with severely affected arm function may indicate that not only in stroke patients but also in PwMS GC may enlarge reaching ROM in different directions. Mean delta values were all positive although rather small with successive GC-HM and GC-HMS. Small improvements in aROM are considered as clinically important as some subjects (5&9) with most severe arm weakness (MI=18) were not able to reach minimal movement requirements of the system in any of the directions without support, while the application of GC helped them to overcome the minimal movement requirements of the system.

Since results point in the direction of a greater ROM with GC, further research regarding this topic seems useful. However adjustments to the system and study methodology will be made, clearly a larger sample size is needed to be able to perform relevant statistical analysis to the data. The minimal movement requirement will be exerted from the software, so it will be possible to more precisely collect data from persons with a very small ROM. To get a broader view on the influence of GC on movement capabilities, also other outcome measures on movement quality will be included beside aROM, such as the hand-path ratio and movement velocity.

Present findings on the effects of anti-gravity support on aROM also invite to verify whether abnormal coupling of shoulder abduction and elbow flexion, that restricts aROM in stroke (Dewald 2001, Beer 2007, Sukal 2007) might also manifest in PwMS[8;10;11]. Beer et al. (2007) found no relation between this abnormal coupling and muscle weakness of the proximal upper limb, nor abnormalities in the balance of elbow flexor-extensor muscle strength in stroke patients. These findings support the existence of abnormal descending motor commands causing this mechanism (Beer, 2007)[8].

As seen in Table 1 the amounts of GC-HM were generally rather small for most MS patients that did not require a Sling. This could lead to issues of motor fatigue when used in a robotic training session. When the goal of such a session is to ameliorate coordination and endurance, many movement repetitions (40-50 or more) are needed (Timmermans, 2009)[14]. When motor fatigue appears too early, it may withhold the PwMS to make sufficient movement repetitions to perform an effective training. In literature, different procedures

to determine GC-HM are found. These are mostly based on the measurement of total arm weight, or on a percentage of this weight. This amount of GC could have an adverse effect so that the arm is supported too much during exercise, what makes a training less effective because no overload is provided (Timmermans 2009)[14].

The present report challenges clinicians and engineers to further investigate optimal procedures for determination of anti-gravity support, enabling patients with upper limb muscle weakness to perform a sufficient amount of training.

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