Abstract—External support of the arm against gravity has a beneficial impact on reaching movements performed by moderately and severely impaired stroke survivors. Provision of scalable gravity compensation may therefore be an important component of robot-based upper limb rehabilitation. This study reports the development and initial evaluation of a scalable gravity-compensated training environment based on the haptic capabilities of the MACARM cable robot. The feasibility of end-point force compensation for gravity torques at the shoulder and elbow is evaluated for movements performed in a vertical plane. Our Progressive Support Training approach is described in detail and the initial results of testing with human subjects are reported.

I. INTRODUCTION

Currently there are over 5.5 million stroke survivors in the United States, with approximately 750,000 people suffering a new or recurrent stroke each year [1]. As evidenced by the large population of stroke survivors with residual motor deficits, rehabilitation of upper limb function has proven elusive. Conventional treatment of the upper limb has typically been based on one of several competing manual manipulation techniques [2]-[4]. However, 3 to 6 months post-stroke, upper limb motor deficits persist in 55 to 75% of patients [5]-[8]. Four years post-stroke, two-thirds of stroke survivors perceive loss of arm function as a major problem [9]. Constraint Induced Movement Therapy (CIMT) and other task-oriented approaches have recently shown promising results, but the required level of residual function has generally restricted successful application to stroke survivors with mild hemiparesis [10]-[12]. There is a clear need to develop more effective therapies for patients with moderate and severe impairment of arm function.

Reaching movements performed by moderately and severely impaired stroke survivors exhibit an extreme sensitivity to mechanical loading. In particular, active support of the arm against gravity has been shown to result in a significant deterioration in movement metrics such as peak velocity, directional accuracy, and active range of motion, relative to performance when the arm is supported by an external device [13]-[15]. The impact of gravity loading on reaching kinematics may reflect, in part, weakness of the anti-gravity shoulder musculature. However, there is compelling evidence that the primary mechanism is related to abnormal coupling between the activations of shoulder and elbow muscles. This coupling results in a progressive decrease in the ability of stroke survivors to generate elbow extension torque or movement with increasing levels of shoulder abduction torque [15]-[16]. These findings suggest that provision of scalable gravity compensation may facilitate upper limb rehabilitation by allowing an increase in rehabilitation intensity and duration, increased active range of motion and associated sensory feedback, and the opportunity to gradually integrate postural support with movement control.

A variety of orthotic devices are available clinically to support the weight of the arm and facilitate rehabilitation and activities of daily living in patients with severe proximal weakness [17]-[19]. However, widely used devices such as the Mobile Arm Support [17] and Balanced Forearm Support [18] do not allow convenient scaling of the amount of gravity compensation. The impact of gravity on post-stroke upper limb movements is task dependent (e.g., movements toward the body are typically less impacted by gravity than reaching movements). Thus, provision of a constant level of compensation during training may be suboptimal. More recently, several passive systems have been developed to provide scalable gravity compensation during upper limb rehabilitation [20]-[23]. Such systems typically use counterweights or spring elements, with manual adjustments required to provide the desired level of gravity compensation.

Robotic devices provide a means to potentially enhance functional recovery by manipulating the mechanical environment in ways that go beyond the capabilities of the human therapist. The efficacy of robot-assisted stroke therapy for the impaired upper limb has generally been supported by the results of recent clinical trials [24]. As such devices gain wider acceptance, provision of software-based gravity compensation may become an important component of rehabilitation. Software-based gravity compensation offers the flexibility to easily modulate the amount of compensation provided in different parts of the workspace, or even to vary the compensation for different phases of a single movement.
In this paper we describe the development and initial testing of Progressive Support Training – a gravity-compensated training protocol developed around the haptic capabilities of the Multi-Axis Cartesian-based Arm Rehabilitation Machine (MACARM). In stroke survivors with moderate or severe impairment, maximum reaching distance deteriorates progressively as loading of the anti-gravity shoulder musculature is increased. Our goal was to develop a robot-based training environment that allowed scaling of the gravity compensation during a single trial, so that patients could perform continuously at the limit of their capability during rehabilitation.

II. OVERVIEW OF THE MACARM

The MACARM is a cable robot based on technology developed by Intelligent Automation, Incorporated (IAI). The prototype MACARM (Figure 1) is configured with eight Active Modules anchored at the corners of a 234 cm (92 in) cube constructed of aluminum extrusion. Each Active Module consists of a high performance motor, a position encoder, a gearbox, a cable spool and a cable fairlead. The end-effector for the prototype system is effectively a 0.51m x 0.33m x 0.05m (24in x 13in x 2in) rectangular prism constructed from tube stock. The Active Modules generate forces that interact with the end-effector through cables, and in this manner, produce forces that interact with the user. User-applied forces are measured directly with a 6 degree of freedom load cell. Mean 3D static accuracy and repeatability over the usable workspace exceed 3 mm and 0.1 mm, respectively.

The MACARM can be operated in either position or force-feedback (admittance) control modes. Both translational and rotational control of the end-effector are supported in the position control mode, while admittance control is currently limited to translational movements. In the admittance control mode, the controller senses the user-applied forces and outputs an updated end-effector position and velocity based on the software model of the desired haptic environment. Incorporation of the Open Dynamics Engine (ODE) software library allows real-time simulation of a vast range of mechanical environments, with the user interacting with the simulated environment via the end-effector. Movement segments with different control modes can be incorporated within a single routine. A library of movement “primitives” supports high-level programming of patient evaluation and training routines. The ability to record, playback, and modify arbitrary paths in 6 degrees of freedom is also supported. For the present study, the subject’s hand was strapped to a gimballed handle and the MACARM was used as a translational device only.

The MACARM incorporates several layers of safety features, including automatic detection of a cable or motor failure, detection of invalid or impossible trajectories, software-based limitations on applied forces, and virtual boundaries (which can be rigid or elastic) on end-effector motion.

Additional details on the design and operation of the MACARM are provided in Mayhew et al. [25].

III. SIMULATION STUDIES

We planned to implement software-based gravity compensation by first mapping the end-point (hand) forces required to provide equilibrium of the passive limb, and then to use the haptic capabilities of the MACARM to render these forces (or a portion thereof) during training of voluntary reaching movements. Given our use of a gimbled handle, the passive arm tends to assume a position in a vertical plane as the end-effector is used to move the hand to various locations in the workspace. The equilibrium problem is therefore approximately 2-D, and horizontal and vertical support forces in the plane of the limb are sufficient to provide equilibrium of the shoulder and elbow under gravity loading. To evaluate the feasibility of using end-point forces to compensate gravity torques at the shoulder and elbow, a series of movement simulations were performed to examine two potentially limiting factors: 1) the force magnitudes required for compensation, and 2) the compensation errors resulting from potential postural differences between the passive mapping and active movement conditions.
A. Required Compensation Forces

The forces at the hand required to compensate gravity torques during point-to-point reaching movements in various parts of the workspace were estimated using a simple two segment model of the upper arm. Mass properties for the upper arm and hand+forearm segments were estimated [26] based on anthropometric measurements taken from an average size male (1.8 m, 80kg). Figure 2 shows representative results for a reaching movement performed in the para-sagittal plane along a horizontal line at shoulder level. As illustrated in Figure 2, the predicted compensation forces were generally of modest magnitude over most of the workspace.

A horizontal traction force is required to offset the elbow flexion torque resulting from the vertical support force, except for hand positions near the torso. This traction force, which ultimately must be transmitted across the glenohumeral joint, increases rapidly near full extension, particularly when a singularity occurs for the straight arm configuration (as in Figure 2). The horizontal traction force is a potential disadvantage of using an end-point (as opposed to exoskeletal) robot for gravity compensation. Patients in our target group frequently exhibit shoulder subluxation, which can potentially be exacerbated by repeated application of traction forces. However, there are currently no well-defined guidelines for acceptable force levels. We decided to implement a 20 N cutoff during force mapping, which is substantially less than arm weight (nominally 5% of body weight [27]) for the typical subject. Based on Figure 2, this should allow force mapping for hand-shoulder distances approaching 90% of arm length, which is adequate for our target population of moderately and severely impaired stroke survivors.

B. Robustness of Gravity Compensation

For accurate gravity compensation during voluntary movement our protocol requires that the shoulder center of rotation be in the same location as during support force mapping. We were concerned that intersession variability in patient positioning or differential trunk and shoulder motions during voluntary movements would lead to unacceptable errors in compensation. To address this issue we determined the compensation errors resulting from misalignment of the shoulder/arm with respect to the mapping position using theoretical support forces determined as discussed above. Specifically, we simulated misalignments of the shoulder center in the anterior/posterior, superior/inferior, and medial/lateral directions and rotation of the limb out of a vertical plane. Figure 3 shows the predicted compensation errors at the elbow and shoulder (flexion/extension degree of freedom) associated with a 2 cm misalignment in each direction. Anterior and inferior misalignments resulted in compensation errors that were approximately mirror images of those associated with posterior and superior misalignments, respectively, and are not shown in Figure 3 for clarity. Predicted compensation errors were small over our target range of motion (90% or arm length). Similarly, rotation of the limb out of the vertical plane (which requires muscle activation in additional degrees of freedom) was associated with small compensation errors. We therefore concluded that endpoint force mapping was sufficiently robust for upper limb rehabilitation.

IV. PROGRESSIVE SUPPORT TRAINING

Our goal was to develop a robot-based training environment that allowed scaling of the gravity compensation during a single trial, so that patients could perform continuously at the limit of their capability during rehabilitation. The Progressive Support Training software we developed is comprised of separate modules that support gravity force mapping (the Calibration Module) and implementation of the gravity compensated training environment (the Training Module). Each module is
discussed in more detail below.

A. Calibration Module

The calibration module generates the routine for mapping of the 3D support forces. Execution of the routine results in passive movement of the limb along a designated path and provides the initial processing of the support force data. In developing the module we tested both slow continuous and incremental movements, and ultimately selected the latter to minimize the potential for voluntary or reflexive muscle activation.

Required operator inputs for force mapping are provided via a Graphical User Interface (GUI). These inputs include the position of the shoulder center relative to the MACARM home position, the initial position of the hand relative to the shoulder, the target direction (defined by angles in the horizontal and vertical planes), the length of the arm, movement distance (as a percentage of arm length), movement increment, hold time at each position, number of cycles, and maximum allowed force. Default values for movement increment and hold time are 2.54 cm (1 inch) and 5 s, respectively.

Upon execution of the routine the subject’s hand is incrementally moved along the target direction through the specified range of motion, held at each position, and returned to the starting position (in a continuous movement) for execution of the next cycle. Forces measured at each position are averaged over the hold period, resolved into horizontal and vertical forces in a vertical plane containing the line of motion, and stored for use as inputs to the Training Module. Sample force data for 3 cycles of movement are shown in Figure 4.

B. Training Module

The training module provides rapid setup of the subject-specific gravity-compensating force-field, randomization of target sequences, tracking of best performances, and storage of performance measures for each trial. In developing the module, we sought to develop a training protocol that would require subjects to maximize reaching distance for levels of gravity compensation which ranged from 0% (no compensation) to 100% during each trial. This was accomplished by implementing the gravity compensating force field in the form of a virtual compliant table. For a given location of the hand in the workspace, the required vertical and horizontal support forces are scaled with the depth of penetration into the table thickness. Thus, for hand positions at or above the top surface of the table no gravity compensation is provided, while 100% compensation is provided at the bottom surface. The thickness of the table is typically set at 10 cm. The force field for each target direction is generated independently based on the results of the calibration routine and is axisymmetric about the shoulder center.

Rapid setup of the training routine is provided by a GUI (see Figure 4). Visualization of the support forces are provided in the interface and the user has the option of choosing the spline order used to fit the data. Other required inputs include the number of shelves (see below), damping force, number of targets, number of blocks and number of trials per block. Additional options are available for further customization of the routine.

The feedback display used for training is shown in Figure 5. Rather than depict the compliant table, discrete support levels are depicted as parallel shelves, which from top to bottom represent increasing levels of gravity compensation. Typically 4 shelves are used, corresponding to 0, 33, 67, and 100% compensation levels. The X (lateral/medial) and Z (up/down) position of the hand is indicated by a circular cursor, the diameter of which decreases with movement of
the hand away from the body. The movement distance along
the target direction, expressed as a percentage of arm length,
is used to characterize performance. Thus, the performance
measure is sensitive to directional control as well as
reaching distance. Feedback of current and best
performances is provided in bar graph and numerical form
(see Figure 5). Sequencing through the shelves is
determined automatically based on evaluation of the hand’s
progression toward the target. A trial ends when the
specified collection time is reached or the hand “contacts”
the lower surface of the table, after which the MACARM
returns the hand to the starting position.

V. HUMAN SUBJECTS TESTS

Five moderately to severely impaired chronic stroke
survivors have been enrolled in pilot testing of the
Progressive Support Training protocol. Upper limb Fugl-
Meyer [28] scores for the subjects ranged from 12 – 30
(mean = 22), out of a maximum score of 66. The primary
inclusion criteria were: 1) unilateral lesion of the cortex or
subcortical white matter with an onset at least one year prior
to participation in the study; 2) absence of severe cognitive
or affective dysfunction; 3) absence of severe concurrent
medical problems (e.g., cardiorespiratory impairment) and
4) mild or no subluxation of the shoulder and an absence of
shoulder pain. The goals of human subjects testing were to:
1) evaluate performance of the MACARM and the
Progressive Support Training software; 2) confirm the
beneficial effects of gravity compensation for movements
performed in the vertical plane; 3) identify any adverse
effects associated with the training and 4) provide
preliminary efficacy data.

Subjects have completed 9-24 training sessions, on a 3
times weekly schedule. Each session was comprised of 30
reaching movements (from a seated position) to each of 3
targets (straight ahead and 22.5° to either side) at shoulder
level. Gravity force mapping was performed immediately
prior to the first training session for the 3 movement
directions and the results stored for use during subsequent
sessions. The nominal starting position of the hand was 25
cm in front of the shoulder center, with the terminal position
ddictated by each subject’s passive range of reaching.
Strapping was used to limit trunk motion during force
mapping and subsequent training sessions. Completion of
gravity mapping required approximately 20 minutes. Each
training session lasted approximately 65 minutes.

Typical support force mapping results are shown in
Figure 4, as well as the cubic spline fits used to generate the
force field. Force magnitude trends with movement distance
were similar to the theoretical curves (see Figure 2),
although for a given absolute reaching distance the traction
forces were less than predicted. This difference is likely due
to movement of the glenohumeral joint during mapping that
was not considered in the theoretical analysis.

During movement training, subjects were instructed to
reach out as far as possible in the target direction without
letting the cursor drop below the level of the top shelf, and
then to continue to reach out while allowing the hand to
drop toward progressively lower shelves as they were
highlighted on the display. Four shelves, corresponding to 0,
33, 67, and 100 % gravity compensation, were used for
training (see Figure 5). Progression to the next shelf
occurred automatically when no increase in reaching
distance was measured during a 1 s interval. A
representative trial for each subject is shown in Figure 6.
For all subjects, maximum reaching distance increased
progressively with increased gravity compensation. This
result is similar to previous findings for movements
performed in the horizontal plane [13]-[15]. However, it
should be noted that in the present study gravity loading
actually assisted elbow extension, yet subjects were still able
to achieve greater reaching distances with gravity
compensation.

All five subjects in the pilot study exhibited mild shoulder
subluxation. As noted earlier, the repeated application of
traction forces is a potential drawback associated with use of
an end-point robot to provide gravity compensation. At each
session, subjects were asked to report any discomfort or pain
that was potentially associated with movement training. To
date, no adverse effects have been reported.

The preliminary evaluation of the efficacy of Progressive
Support Training will be based on pre/post training
comparisons of reaching kinematics after all subjects have
completed 24 training sessions. This component of our pilot
study will be completed in the 3rd quarter of 2008.

VI. CONCLUSION

Our initial experience with Progressive Support Training
has been encouraging. Given the required traction forces on
the limb, the application of our method to patients with more
severe subluxation or other shoulder problems requires further study.

Future technical work will focus on tracking of shoulder position to allow shifting of the gravity compensation force field with translation of the shoulder and trunk, development of more game-like training protocols which incorporate gravity compensation, and generalization of our approach to more complex movements.

REFERENCES