accommodate the peak tangential velocities seen at the forearm and upper arm during ballistic movements in mildly impaired subjects (Beer et al. (2004) Exp. Brain Res. 156: 458-470). The HAPTICMASTER device was redesigned to accommodate these movement velocities. The basic drive mechanisms of the three primary axes were modified to accommodate the new requirements. This was accomplished by selecting a different drive motor, in this case a brush type servo motor, or by changing the force transmission consisting of a lead screw, or a combination thereof. The lead crews were placed such that one screw was directly connected to a drive motor and this combination is used to drive one axis. Since there are three axes there are also three motor/lead screw combinations. Drive motor and lead screw changes can affect the output torque and speed of each axis. This makes it possible to select a combination of motor and lead screw suitable to the requirements of each of the three axes.

Example II

Impairment Quantification

[0217] Reaching in a plane was explored using the system while concurrently measuring shoulder/elbow/wrist and finger forces and torques. This allowed back calculation of shoulder and elbow torques as well as wrist and finger forces/torques, which is a highly relevant output measure of the system. The system also allowed for the monitoring of higher speed movements during which subjects were able to perform ballistic reaches in several conditions: fully supported by a rigid plane passing though the center of rotation of the shoulder, and with various levels of support that virtually reduce or enhance gravity. Subjects were asked to move to a variety of targets within a plane that passes through the center of rotation of the shoulder. These targets encompass both reach and retrieval directions, and the plane can be horizontal, inclined or declined. In this way, the ACT^{3D} system can characterize fast point to point movements in several aspects of the total work volume while also monitoring wrist and finger kinetics and/or kinematics.

[0218] To reduce the impact that hyperexcitable stretch reflexes (or spasticity) may also have on the compromised arm, another protocol emphasizes slow movements. Subjects were asked to slowly make the largest circle they could with their arm. Like the ballistic reaching protocol, this was done under rigid support from a haptic table, or while the subject was concurrently producing particular levels of active limb support. By reducing the impact of spacticity, the best picture of available work area was constructed. We conducted some experiments using the above protocol with adult hemiparetic stroke subjects; **FIG. 10** shows an example of the results obtained. **FIG. 10A** shows work areas a left hemiparetic subject was able to achieve with their impaired limb (the x-axis has been inverted for comparison with the right side). As active limb support increases, there is a marked decrease in available work area. **FIG. 10B** shows the results from their unimpaired side. In the unimpaired side, there was no effect of limb support (**FIG. 10B**). However, in the impaired side there was a clear cost for increased levels of active limb support, and therefore shoulder abduction torques (**FIG. 10A**). Work area decreased significantly as subjects were required to lift more of their limb weight; this was a direct effect of decreases in elbow extension range as illustrated on **FIG. 11** for twelve moderate-to-severely impaired stroke subjects, with elbow flexion capabilities preserved across support levels. **FIG. 11** compares the unimpaired (left bar, blue) and impaired (right bar, red) limb work areas, normalized to the table supported condition revealed a significant difference between limbs in all levels of support (*$p<0.05$; **$p<0.001$).

[0219] The results were obtained at the horizontal plane at 90 degrees of shoulder abduction. This protocol-can be extended into inclined and declined planes in the same way as the ballistic reaching protocol. Using the information collected by the ACT^{3D}, a complete characterization of available shoulder and elbow angle and torque combinations and resulting 3-D workspace during different levels of support and at different plane inclination angles were constructed for each subject.

Example III

Therapeutic Intervention

[0220] Under the guidance of our gravity-induced discoordination concept, several therapeutic intervention protocols can be realized. A protocol in which gravity was progressively re-introduced during outward reaching over a period of eight weeks was used. More specifically, subjects were trained to reach outward towards virtually displayed targets that were situated on a horizontal plane associated with the height of the shoulder. The targets required near full active range of motion to acquire. The key component of the training was the progressive re-introduction of gravity as the subject improved in their capacity to acquire each target. Furthermore, gravity was re-introduced in an aggressive fashion. Subjects performed three sets of ten repetitions to each of five targets under the amount of gravity or limb support that maximally challenged them to reach at least 50% of the distance toward the target. Each target ultimately had its own gravity setting and appeared to progress at its own rate in terms of increasing the gravity setting on the following session as the subject was able to reach farther toward the target. The effect of gravity re-introduction training on motor performance is studied by comparing this protocol with a similar protocol where active support of the limb against gravity is not required. In this comparison group, subjects reach toward the same targets but are supported by a haptically rendered horizontal surface associated with the height of the shoulder. Each group participates in eight weeks of training at a frequency of three sessions per week. By comparing group performance on the metrics mentioned in the previous section, the effect of re-introducing gravity is elucidated. An example of a positive effect of the gravity reintroduction protocol is shown for a single subject in **FIG. 12**. **FIG. 12** shows hand path traces pre (**FIG. 12A**) and post (**FIG. 12B**) training, with three support levels shown. Note the increase in work area at 175% of limb weight using the work area measurement discussed earlier.

Example IV

Interface Between the Paretic Limb and the HAPTICMASTER

[0221] The forearm of the stroke survivor was placed on a support splint that was attached via a three degree-of-freedom (3-DOF) gimbal axis system to the end of the robot.