smoothly and rapidly in compliance with a patient's actions (Lawrence (1988) Proc. IEEE Int. Conf. Robotics & Automation 1185-1191).

[0016] In contrast to commercial robotic technology, the MIT-MANUS robotic device was specifically designed for clinical neurological applications (Hogan et al. (1995) J. Interactive Robotic Therapist). The MIT-MANUS robotic device is configured for safe, stable and compliant operation in close physical contact with humans. Its computer impedance control (synonymous with position control) system modulates the way the robot reacts to mechanical perturbation from a patient or clinician and ensures a gentle compliant behavior (technically, a low and controllable impedance) (Hogan (1985) ASME J. Dynamic Systems Measurement and Control 107: 1-24). Operationally, a low impedance means that the robot can "get out of the way" as needed. However, due to the impedance control system, there is a moderate level of resistance due to inertia that the user must overcome to produce movement. This attribute limits the applicability of the MIT-MANUS to subjects who are able to exert enough force to overcome the inertial resistance of the device.

[0017] To test the feasibility of robot-aided neuro-rehabilitation, MIT investigators have used the MIT-MANUS robotic device in pilot studies on a daily basis for over seven years with CVA (cerebral vasculary incidence resulting in a stroke), Parkinson's disease, multiple sclerosis, spinal cord injury, amyotrophic lateral sclerosis (ALS), and Guillain-Barré (GB) patients at the Burke Rehabilitation Hospital. The key research objective in these pilot studies was to validate the concept of robot-aided exercise therapy and assess whether: (a) robot-aided therapy had adverse effects, (b) patients would tolerate the procedure, and (c) manipulation of the impaired limb influenced motor recovery. The results in these pilot clinical trials with 96 stroke patients showed that robot-aided neuro-rehabilitation did not impede recovery or exacerbate joint or tendon pain, and no adverse events occurred in an estimated 2000 hours of operation involving close contact with patients. A questionnaire administered during the bi-weekly standard assessment by the therapists showed that robot-assisted therapy was well accepted and tolerated by the patients. Most important, results indicated that patients in the experimental group improved further and faster, outranking the control group in the clinical assessments of the motor impairment involving shoulder and elbow. (See, for example, Aisen et al. (1997) Arch. Neurol. 54: 443-446; Krebs et al. (1998) IEEE Transact. Rehab. Engineer. 6: 75-87; Krebs et al. (2000) VA J. Rehab. Res. Dev. 37: 639-652; Volpe et al. (2001) Curr. Opin. Neurol. 14: 745-752; Volpe et al. (2000) Neurology 54: 1938-1944, and Ibid. (1999) Neurology 53: 1874-1876). However, a shortcoming of the MIT-MANUS obviating its usefulness for application in the evaluation and rehabilitation of gravity-induced discoordination is that it only works in a horizontal plane unable to provide various levels of limb support or operate in all directions of movement. In addition, impedance control technology must use a very light structure which may contain mechanical shortcomings such as friction or mechanical compliance. Even though forces may be measured at the patient interface, no compensation can be made for such non-linearities since they occur between the force control device, the motor, and the patient introducing errors that cannot be compensated.

[0018] Several similar US Patents have been issued to the above technology. For example, U.S. Pat. No. 5,466,213 to Hogan et al. is directed to an interactive robotic therapist that guides a patient's limb along a desired path through a desired series of exercises. The robotic therapist incorporates sensors that provide position, velocity, and force information at the patient's hand. The reference, however, does not teach using-force and position information in both real and virtual environments to measure, treat, or self-rehabilitate impaired movement performance.

[0019] U.S. Pat. No. 5,421,798 to Bond et al. is directed to an apparatus for evaluation of a limb of a test subject. The distal end of the limb is secured to the apparatus. The test subject moves the limb along a linear track. At least two components of the forces generated by the limb against the track are sensed. The force components are used to calculate the forces applied at each limb joint contributing to movement. The reference, however, does not teach using force and position information in both real and virtual environments to measure, treat, or self-rehabilitate impaired movement performance.

[0020] U.S. Pat. No. 5,830,160 to Reinkensmeyer is directed to a movement guiding system for quantifying, diagnosing, and treating impaired movement performance. The guiding system guides movement of a limb along a linear path and can quantify movement performance by measurting constrqaint forces generated during the movement. The reference does not teach force and position information in both real and virtual environments to measure, treat, or self-rehabilitate impaired movement performance.

[0021] U.S. Pat. No. 6,413,190 to Wood and Koval is directed to a rehabilitation apparatus and method that monitors patient rehabilitation thaearapy activity, the apparatus detecting sequential muscle contractions thereby operating a computer game that reflects the movement upon a screen. The patient is therefore encouraged to ensure that two muscles move in a temporal sequence to "play" the game. The reference does not teach using force and position information in both real and virtual environments to measure, treat, or self-rehabilitate impaired movement performance.

[0022] U.S. Pat. No. 4,936,299 to Erlandson discloses a rehabilitation apparatus having a robotic arm controlled by application software and a control board of a CPU. The patent also discloses a viewing screen and that the rehabilitation is initiated and under direction of a therapist. The reference does not teach using force and position information in both real and virtual environments to measure, treat, or self-rehabilitate impaired movement performance.

[0023] U.S. Pat. No. 6,613,000 to Reinkensmeyer discloses a system providing arm movement therapy for patients with sensory motor impairments having a joystick controlled by application software of a CPU over the World Wide Web using client-side applets. The patent also discloses a viewing screen and that the rehabilitation is performed without the direction or supervision of a therapist but in response to a predetermined desired therapeutic exercise. The reference does not teach using force and position information in both real and virtual environments to measure, treat, or self-rehabilitate impaired movement performance.