nearly identical ground reaction estimates as compared to the ground truth (ideal) ground reaction forces obtained by an Iterative Newton Euler inverse dynamics procedure.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0036] The present invention provides computational methods for analysis, and synthesis of human motion under partial assist from powered augmentation devices. The algorithms are integrated in a simulation platform to be used as a test-bed for prototyping, simulating, and verifying algorithms to control human motion under artificial control. The analysis and synthesis problems in human motion are formulated as a trajectory tracking control algorithm using inverse and forward models coupled by proportional and derivative feedback terms. A muscle force distribution and capacity module is used to monitor the computed joint torques in order to assess the physiological consequences of the artificial control, and if needed to make modifications. This framework allows us to verify robustness, stability, and performance of the controller, and to be able to quickly change parameters in a simulation environment. We can study many different motions in a simulation environment. Thus, future performance and designs of human augmentation devices can be studied through simulation, without the risk and constraints imposed by hardware implementations of current technology.

[0037] The System Model

[0038] The system (or plant) refers to a dynamic model of the combined musculoskeletal and augmentation device system. The system may be designed having various degrees of complexity, depending on the requirements imposed by the study. Without loss of generality, we consider a simple planar biped system to illustrate the concepts (See **FIG. 1**). The equations of motion are formulated in such a way to handle three phases of biped motion as shown in **FIG. 1**. They include single support, double support, and airborn. Let q be the coordinates corresponding to the rotational and translational degrees of freedom.

$$q=[x_3 y_3 \Theta_1 \Theta_2 \Theta_3 \Theta_4 \Theta_5]^T \tag{1}$$

[0039] where (x_3, y_3) corresponds to the center of mass of the torso and the joint angles Θ are measured clockwise from the vertical.

[0040] The system is actuated by voluntary control from the muscles and artificial control from the augmentation device. The total torque applied at the joints (net joint torque) are the combined torque from the muscles (τ_m) and the assist actuators (τ_a)

$$\tau=\tau_a+\tau_m \tag{2}$$

[0041] Let C(q) represent the foot-floor contact constraints and $\Gamma=[\Gamma_L \Gamma_R]^T$ be the vector corresponding to the ground reaction forces under the left and right feet. The equations of motion of the system are given by,

$$J(q)\ddot{q} + B(q, \dot{q})\dot{q} + G(q) + T_{ad} = \frac{\partial C^T}{\partial q}\Gamma' + D\tau \tag{3}$$

[0042] where J, B, and G correspond to the inertia, coriolis and centrifugal torques, and gravitational terms, respectively. The vector T_{ad} models the augmentation device dynamics and the constant matrix D characterizes the torque coupling effects at the joints. The matrix D is present because absolute coordinates for the joint angles are used in the formulation of the equation of motion, as opposed to relative coordinates. The ground reaction forces may be expressed as a function of the state and inputs by (Hemami, H., A feedback On-Off Model of Biped Dynamics. IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-10, No. 7, July 1980).

$$\Gamma = \left(\frac{\partial C}{\partial q} J(q)^{-1} \frac{\partial C^T}{\partial q}\right)^{-1} \left(-\frac{\partial}{\partial q}\left(\frac{\partial C}{\partial q}\dot{q}\right)\dot{q} + \frac{\partial C}{\partial q} J(q)^{-1}(B(q, \dot{q})\dot{q} + G(q) + T_{ad} - D\tau)\right) \tag{4}$$

[0043] **FIG. 2** shows a system model description with intermittent contact of left and right feet with the ground. Forward dynamic simulations are performed by computing the induced accelerations $\ddot{q}$ obtained from Equation 3 and Equation 4, using the simulated state variable q and $\dot{q}$ which are obtained by numerical integration.

[0044] The Internal (Inverse) Model

[0045] It has been demonstrated that the behavior of the human body when coupled with a novel mechanical system is very similar to the behavior that results when the controller relies on an internal model. One such internal model is thought to be a forward model, a term used to describe the computations involved in predicting sensory consequences of a motor command. There are a number of studies that have suggested that a forward model may be used by the human central nervous system (CNS) to estimate sensory consequences of motor actions (Wolpert, D. M., Miall, R. C., Kerr, G. K., Stein, J. F. Ocular limit cycles induced by delayed retinal feedback. Exp Brain Res., 96: 173-180, 1993; Flanagan. J. R., Wing, A. M. The role of internal models in motion planning and control: evidence from grip force adjustment during movements of hand held loads. J. Neurosci, 17:1519-1528, 1997). This theory is easily understood when considering transmission delays inherent in the sensory-motor loop. Although a forward model is particularly relevant to feedback control of time delayed systems, an inverse model is sometimes considered to predict the motor commands that are appropriate for a desired behavior (Atkeson, C. G. Learning arm kinematics and dynamics. Annu Rev. Neurosci, 12:157-183, 1989; Kawato, M., Adaptation and learning in control of voluntary movement by the central nervous system. Advanced Robotics 3, 229-249, 1989; Shadmehr, R., Leaming virtual equilibrium trajectories for control of a robot arm. Neural Comput, 2:436-477, 1990; Gomi, H., Kawato, M., The cerebellum and vor/okr learning models. Trends Neurosci, 15:445-453, 1992).

[0046] Inverse models are generally not considered for control of time delayed systems since the controller would seem to not have the ability to respond to the error and results in instability. However, it is plausible that local or intrinsic feedback mechanisms in conjunction with an inverse model can function to stabilize a system with latencies. Local feedback with stabilizing characteristics is