

Posture Prediction with External Loads – A Pilot Study

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ABSTRACT

As the need for more advanced human modeling tools has grown, so has the focus on research and development with posture-prediction capabilities for the design and analysis of products, and for the study of human behavior. Virtual humans have grown from digital mannequins with limited fidelity, to realistic avatars with predictive capabilities. Now, one of the frontiers with posture prediction is the incorporation of external loads and joint torques. Although advancements have been made with dynamic motion prediction, relatively little work has been conducted with external load-based posture prediction. Drawing on past success with optimization-based kinematic posture prediction implemented with the virtual human SantosTM, we present a new method for considering external loads. A pilot study is conducted whereby equations for static equilibrium are incorporated in the optimization formulation. Consequently, torque (as well as joint angles) is determined for each degree of freedom, and is incorporated in human performance measures that serve as objective functions in the optimization formulation. The intent is to test the feasibility of extending the formulation for kinematic posture prediction. Different external loads are applied to the right and left hands respectively, while the same target points are provided for these different load cases on both hands. The results for the previous work (kinematic formulation) and the new formulation are compared. The predicted postures are evaluated quantitatively in terms of numerical

output, and subjectively in terms of visible postures. In general, the pilot study was successful; the predicted postures were reasonable. Including torque provided more realistic predicted postures and sets the stage for new discomfort models as well as consideration of reaction forces.

INTRODUCTION

Digital human models (DHMs) provide efficient tools for product and process design, and human analysis. Such tools allow one to assess human-product interaction in a virtual environment in order to reduce design-cycle time and cost while increasing safety. As DHM technologies advance, potential applications expand to areas such as military, medicine, sports, etc. With many applications, one of the most essential capabilities is fast and accurate posture prediction and analysis. And, a critical component of human posture prediction is the incorporation of joint torques with applied loads. However, there has been minimal work with actually considering external loads in computational predictions of human posture. Thus, the primary objectives of this paper are 1) to test the feasibility of incorporating applied loads in optimization-based posture prediction, and 2) to test basic torque-based human performance measures that provide the objective functions for optimization-based posture prediction. This work is intended as a pilot study for further development of posture prediction capabilities.

With regards to methods for predicting posture, there are two main approaches: data-based approaches and analytical inverse kinematics (IK) approaches. With data-based approaches, one uses prerecorded motion data, anthropometric data, and functional regression models (Beck and Chaffin, 1992; Zhang and Chaffin, 1996; Faraway, 1997; Chaffin *et al.*, 1999; Chaffin, 2002). This approach tends to be resource intensive and can be limited by the database being used.

Analytical IK approaches predict posture by using analytical methods to simulate human motion. However, as the number of degrees of freedom (DOFs) increases, traditional analytical methods become intractable. In such cases, optimization-based methods become more prudent.

Zhao and Badler (Zhao *et al.*, 1994) provide one of the earliest approaches that directly incorporate optimization for posture prediction. A gradient-based unconstrained optimization routine is used to minimize the weighted sum of components that model various factors, such as the position of the end-effector (a specified point, line, or plane) or the orientation of the hands. Riffard and Chedmail (Riffard *et al.*, 1996) use a similar approach and determine the optimum placement of the torso and the optimum posture of a seven-DOF arm, using simulated annealing, which is a global optimization method. Equations for target contact, collision avoidance, vision, body-orientation, and torque are combined in a weighted sum to form the objective function. These methods involve optimization algorithms for unconstrained problems, so constraints must be included in the objective function as penalty terms. Consequently, the extent to which one uses the objective function to model what drives human performance is limited. Yang *et al.* (2004; 2006) provide an optimization-based approach that leverages constrained optimization and uses a relatively complex human model based on DH-method (Denavit and Hartenberg, 1955). This approach predicts posture in real time and allows for a relatively large number of DOFs. There is no difficulty in altering model parameters and seeing the consequences in the simulation.

With regards to analyzing postures once they have been predicted or simulated, currently available computational methods are limited. Because posture selection during forceful exertions has a strong relationship between hand-force and posture (Haslegrave *et al.*, 1997), and because external forces are involved in almost any working posture, posture prediction with external loads and joint torques has become a significant frontier. The 3D Static Strength Prediction Program (3DSSPP) is one of the earliest models for calculating joint strength (Chaffin *et al.*, 1991; Chaffin, 1997). This involves a twelve-link model to determine static biomechanical estimates of joint moments, spinal compression forces, and balance for sequential static postures from motion models. It involves the analysis of a predetermined postures (actual posture

prediction is not involved), and the skeleton model is relatively simple. OpenSim (Delp *et al.*, 2007) is open source software that allows users to develop models of musculoskeletal structures and create dynamic simulations of a wide variety of movements. Variables such as joint torques and muscle forces are calculated with pre-recorded movement of a human body. This is only a simulation model, and it cannot predict posture or motion.

With regards to motion prediction, there has been a substantial amount of work completed. Recently, an optimization-based predictive dynamics method has matured for predicting dynamic motion with different tasks such as walking (Xiang *et al.*, 2007), lifting (Xiang *et al.*, 2008), and stair-climbing (Bhatt *et al.*, 2008). However, although advancements have been made with dynamic motion prediction, relatively little work has been conducted with incorporating external loads in posture prediction.

Given that discomfort is often considered a primary factor in dictating human posture, it is a necessary consideration with any development of posture-prediction capabilities. In fact, some literature suggests that joint torque should be combined with posture prediction capabilities in order to predict human posture more accurately, and joint torques can only be calculated if applied loads are incorporated in the predictive models. Allread *et al.* (1998) perform experiments to evaluate discomfort in manufacturing environments and find that overall total-body discomfort depends on external loads. Santos *et al.* (2000) conduct experiments to correlate subjective indications of discomfort with biomedical indices that are evaluated using a 54-DOF motion-capture model. The authors find a linear relationship between discomfort and the following two biomedical indices: 1) the deviation from a neutral position, and 2) the moments in the muscles that are necessary to counter the effect of gravity. Other authors also suggest that joint stresses and loads provide an additional factor for modeling discomfort (Kayis and Hoang, 1999; Bubb and Estermann, 2000). Zacher and Bubb (2004) draw similar conclusions with respect to a proposed force-based discomfort model. They find that discomfort depends on the magnitude and direction of forces at the joints. Although much experimental work has been completed regarding joint torque and posture, there are currently no computational posture-prediction models involving joint torque.

In general, there has been no work to combine posture-prediction capabilities with applied loads. Physics based posture prediction is currently unavailable and is clearly needed. Although accurate for single subjects, data-based posture prediction lacks autonomy. Traditional analytical approaches to IK are impractical for complex human systems, and they are not physically accurate (static equilibrium is not considered). Currently available static analysis tools are not predictive. Consequently, there is a distinct need for a real-time computational approach to posture prediction that incorporates applied

loads, calculates joint torques, and provides useful feedback.

Overview of the Paper

This paper leverages success at The University of Iowa's Virtual Soldier Research (VSR) Program in developing SantosTM, a highly realistic predictive human model (Abdel-Malek *et al*, 2006; Yang *et al*, 2007). Santos uses an optimization-based approach to posture prediction, and this paper presents a new method for incorporating equations of static equilibrium in this approach. First, an overview of optimization-based posture prediction is provided. Then, a detailed optimization formulation is developed for an upper-body model, which incorporates applied loads, static equilibrium, and torque-based performance measures (objective functions). Basic examples are run with loads applied to both hands simultaneously. The results are evaluated quantitatively in terms of numerical output, and qualitatively in terms of visual outputs. Finally, contributions are summarized, high level issues and challenges are discussed, and future work is presented.

OPTIMIZATION-BASED POSTURE PREDICTION

This section provides an overview of the current optimization-based approach to posture prediction. The human skeletal system is highly redundant from a kinematics perspective, meaning there are infinitely many postures one can assume in order to contact a single target point. This means there are infinitely many solutions to most inverse kinematics problems (determine human joint angles necessary to contact specified Cartesian points) involving the human body. However, it is possible to determine a single realistic posture by using optimization.

Simulating human posture depends largely on how the human skeleton is modeled. We view a skeleton as a series of links with each pair of links connected by one or more revolute joints. Therefore, a complete human body can be modeled as several kinematic chains, as shown in Figure 1.

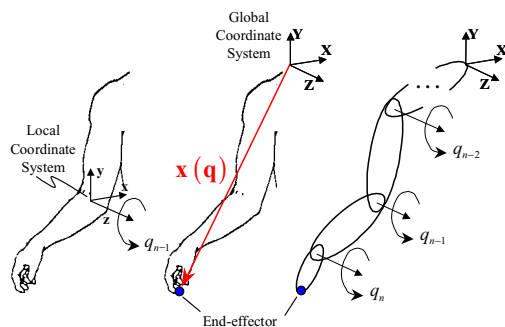


Figure 1: A kinematic chain of joints

q_i is a *joint angle* and represents the rotation of a single revolute joint. There is one joint angle for each DOF. $\mathbf{q} = [q_1, \dots, q_n]^T \in R^n$ is the vector of joint angles in an n -

DOF model and represents a specific posture. Each skeletal joint is modeled using one, or more kinematic revolute joints. $\mathbf{x}(\mathbf{q}) \in R^3$ is the position vector in Cartesian space that describes the location of the end-effector with respect to the global coordinate system. For a given set of joint angles $\mathbf{q}$, $\mathbf{x}(\mathbf{q})$ is determined using the Denavit-Hartenberg (DH)-method (Denavit and Hartenberg, 1955). The DH-method uses a series of transformation matrices to translate from joint space to Cartesian space.

With this pilot study, a 55-DOF model for the human torso, right arm, left arm, and neck is used as shown in Figure 2, where each cylinder represents a rotational DOF. This also includes six global DOFs, three for translation of the hip point and three for rotation about the hip point. The posture of this model is determined by solving the optimization problem developed at VSR and formulated in this section. The design variables for the problem are q_i , measured in units of radians.

The first constraint, called the *distance* constraint, requires the end-effector to contact a target point. In addition, each joint angle is constrained to lie within predetermined limits. q_i^U represents the upper limit, and q_i^L represents the lower limit. These limits are derived from anthropometric data.

The basic benchmark performance measure represents joint displacement (Jung *et al*, 1994; Mi *et al*, 2002). This performance measure is proportional to the deviation from a *neutral position*, which is selected as a relatively comfortable posture, typically a standing position with arms at one's sides. q_i^N is the neutral position of a joint. Because some joints articulate more readily than others, a weight w_i is introduced to stress the relative stiffness of a joint. Additional performance measures can also be used, such as musculoskeletal discomfort (Yang *et al*, 2004; Marler *et al*, 2005), potential energy (Yang, *et al*, 2004; Marler, 2005), and visual displacement (Marler *et al*, 2006; Smith *et al*, 2008).

The optimum posture for the system shown in Figure 2 is then determined by solving the following problem:

$$\text{Find: } \mathbf{q} \in R^{DOF} \quad (1)$$

$$\text{To minimize: } f_{\text{JointDisplacement}}(\mathbf{q}) = \sum_{i=1}^n w_i (q_i - q_i^N)^2$$

$$\text{subject to: Distance} = \|\mathbf{x}(\mathbf{q})^{\text{end-effector}} - \mathbf{x}^{\text{target point}}\| \leq \varepsilon$$

$$q_i^L \leq q_i \leq q_i^U; i = 1, 2, \dots, DOF$$