Optimization-Based Posture Prediction for Analysis of Box Lifting Tasks

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Abstract. New methods for optimization-based posture prediction with external forces are presented and tested. The proposed approach incorporates prediction of 113 degrees of freedom including global position and orientation of the body as well as foot position, while considering balance. Postures and joint torques are successfully predicted and compared to motion-capture data and literature-based data respectively. This approach is applied to a box-lifting task and provides a robust tool for studying human performance and for preventing injuries.

Keywords: Posture prediction, optimization, box lifting, joint torque.

1 Introduction

In an effort to address potential pain and injury associated with box-lifting tasks, new developments with optimization-based posture prediction not only reflect research but also yield a unique and versatile tool for predicting and analyzing human performance. Especially within the manufacturing arena, data-based ergonomic tools help assess the risks associated with demanding tasks. While these tools provide well accepted standards, they are limited in the types of scenarios to which they apply. Furthermore, traditional human modeling tools are limited in their predictive capabilities and versatility. Consequently, this paper presents new posture-prediction capabilities that are successfully applied to tasks like box lifting. Two novel predictive components are presented in the context of the optimization-based posture-prediction approach developed at University of Iowa's Virtual Soldier Research (VSR) Program: 1) whole-body posture prediction including global position and orientation, which inherently includes prediction of foot position, and 2) posture prediction with external forces, which includes incorporation of balance and torque-based performance measures.

While research with reach analysis and human posture analysis is extensive, relatively little work has been completed with real-time human posture prediction, especially with a whole-body model. The proposed work centers on a whole-body predictive human model that includes a total of 113 predicted degrees of freedom (DOFs). In addition to the underlying kinematic posture-prediction model, we present methods for incorporating external forces. In this way, the mass of body segments and

V.G. Duffy (Ed.): Digital Human Modeling, HCII 2011, LNCS 6777, pp. 151–160, 2011.

of components in the virtual environment are considered. Finally, various new torque-based performance measures are implemented to study the effects of joint torque on human performance. This improves realism substantially when modeling tasks such as box lifting. The consequent predictive capabilities provide realistic results visually and objectively. The predicted torques are well within literature-based results. The ability to predict posture for a large number of DOFs; to predict overall body position and orientation, including foot position; and to predict joint torques while respecting balance restrictions are significant contributions.

The fields of posture prediction and box-lifting analysis have both received considerable attention in the DHM community. As Marler *et al* (2005) and Marler *et al* (2008) summarize, the field of posture prediction has fostered three primary approaches: data-based approaches (Farraway, 1997; Chaffin *et al*, 1999), analytical inverse kinematics (IK) approaches, and optimization-based approaches (Zhao *et al*, 1994; Riffard *et al*, 1996, Mi *et al*, 2002; Farrell *et al*, 2005). While data-based methods can capture the realistic nuances of human motion, they tend to be resource intensive. Analytical approaches are becoming less common because of the limitations in the scale of the model that can be used. If formulated and validated properly, optimization based methods can provide realistic and computationally fast results for complex systems, and can provide unique tools for studying how and why humans behave the way they do.

Optimization-based approaches allow one to study how different performance measures (used as objective functions) drive human postures (Marler, 2005; Marler *et al*, 2005b; Marler *et al*, 2009), but minimal work has been done with torque-based objectives. Although some optimization-based methods depend on unconstrained formulations (Zhao *et al*, 1994; Riffard *et al*, 1996), it can be helpful to separate out objective functions and constraints. The objectives represent what drives human performance, and the constraints represent the boundary conditions of the problem.

Some literature suggests that joint torque should be combined with posture prediction capabilities in order to predict human posture more accurately (Allread *et al*, 1998; Santos *et al*, 2000; Zacher and Bubb, 2004), and joint torques can only be calculated if external forces are incorporated in the predictive models. Although much experimental work has been completed regarding joint torque and posture, there are few computational posture-prediction models involving joint torque.

Kim *et al* (2009) use the Santos model and the approach presented by Liu *et al* (2009), to develop a balance constraint for seated conditions, which involves calculating joint torques. Although a whole-body model is developed, the global degrees of freedom and the lower limbs are essentially frozen during the posture-prediction process. The visual results are similar to those presented by Marler *et al* (2007). Yang and Kim (2010) use the same underlying human model as Kim *et al* (2009), and simplify the work of Kim *et al* (2008) for static cases as did Liu *et al* (2009). This work focuses on a method for calculating joint-torques of a pre-defined posture, for standing and seated cases. The test cases are similar to those used by Liu *et al* (2009) and Marler *et al* (2007). Liu *et al* (2009) presents a method for optimization-based posture prediction with external forces. However, it does not use a whole-body model for the predictions, and it does not consider balance. Thus, the proposed work is and extension of the methods presented by Liu *et al* (2009).

The literature analyzing box-lifting tasks is extensive, responding primarily to the need to reduce potential injuries. Two common tools for such analysis are the NIOH lifting equation (Waters *et al,* 1994) and the Liberty Mutual Lifting Tables (Snook and Cirello, 1991). However, these tools are static and limited with respect to the scenarios to which they apply. Alternatively, in the context of complete DHM tools, some work has been done with dynamic motion prediction (Chang, *et al* 2001; Kim *et al*, 2005; Xiang *et al*, 2009). While dynamic motion prediction provides the most accurate analysis of box lifting tasks (Wagner *et al*, 2007), the work in this paper provides expanded and fast posture-prediction capabilities with broad applications defined on the fly by the user, in order to bridge the gap between data based tools and dynamic simulations.

2 Method: Posture Prediction with External Forces

This section provides an overview of the underlying human model, the conceptual formulation for posture prediction with external forces, and a summary of the technical components of the formulation.

The work presented in this paper uses the Santos human model (Abdel-Malek *et al*, 2004) as a platform for further development. The underlying skeletal structure for Santos™ is modeled as a series of links with each pair of links connected by one or more revolute joints (Figure 1).

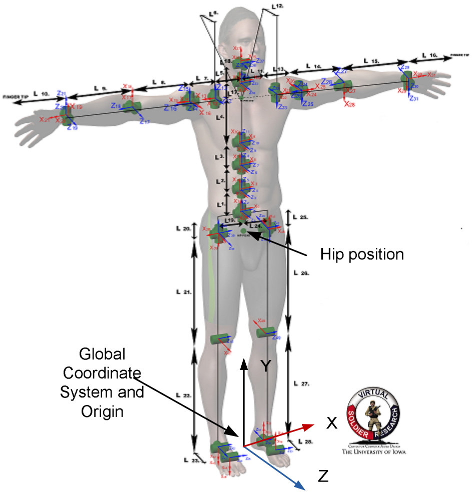

Fig. 1. The Santos Model

There is one joint angle for each DOF, and the relationship between the joint angles and the position of points on the series of links (or on the actual avatar) is defined using the Denavit-Hartenberg (DH)-notation (Denavit and Hartenberg, 1955).

This structure is becoming a common foundation for additional work in the field of predictive human modeling and has been successfully used with other research efforts (Ma *et al*, 2009; Howard *et al*, 2010; Yang and Kim, 2010).

Given the structure in Figure 1, postures are predicted using an optimization-based approach detailed by Marler (2005). Joint angles serve as the design variables, which are incorporated in various objective functions and constraints, the fundamental formulation for which given as follows:

Find: $\mathbf{q} \in R^{DOF}$

To minimize: $f\left(\mathbf{q}\right)$

Subject to:

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

$$q_i^L \leq q_i \leq q_i^U;\ i = 1,2,\text{K}\ ,DOF$$

q is a vector of joint angles, ***x*** is the position of an end-effector or point on the avatar, ε is a small positive number that approximates zero, and DOF is the total number of degrees of freedom. With this study, a single model with 113 DOFs is used for the human torso, arms, legs, neck, hands, eyes, and global position and orientation. *f(q)* can be one of many performance measures (Marler *et al*, 2005; Marler *et al*, 2005b; Marler, 2005; Marler *et al*, 2009). The primary constraint, called the *distance* constraint, requires the end-effector(s) to contact a specified target point(s). q_i^U represents the upper limit, and q_i^L represents the lower limit. These limits are derived from anthropometric data. In addition to these basic constraints, many other constraints can be used as boundary conditions to represent the virtual environment.

This optimization problem can include a series of additional constraints created by the user on the fly, in order to simulate infinitely many tasks. Automatically including the global DOFs allows one to predict the position and orientation of the body. Consequently, this is not just a method for inverse kinematics of human limbs. It is a method for simulating human performance. During the posture prediction process, the feet are not fixed to one location. Rather, they are constrained to a bounded plane that represents the ground, so the optimum (most realistic) foot position is automatically predicted in real time.

2.1 Formulation

This section uses the basic structure presented above, and develops a new approach for posture prediction with external forces. The conceptual formulation is outlined as follows:

Given:

1) End-effectors and associated target points/lines/planes
2) External loads
3) Position and orientation of ground

Find:

Joint angles

To minimize:

Joint torques and/or joint displacement

Subject to:

1) Distance constraints involving given target points/lines/planes
2) Joint limits
3) Torque limits
4) All contact points remain on the contact plane
5) Balance
6) Static equilibrium, including body mass, external forces, and ground reaction forces

The mathematical formulation is outlined as follows and is solved using the SNOPT software (Gill *et al*, 2002), with analytical gradients determined for all objective functions and for all constraints.

Given:

1) Target point & end-effector: $x^{end-effector}$,
2) External loads at given positions: $[F_k \quad M_k]$ at position ${}^k r_k$ for link *k*
3) Contact plane: specified with point p_{ground} and normal n_{ground}

Find:

Joint angles:

To minimize:

Joint torques: $$f(\tau(q)) = \left(\sum_{i=1}^{DOF}\left(\left(\frac{\tau_i}{\tau_i^U - \tau_i^L}\right)^2 + 1\right)^p\right)^{\frac{1}{p}}; p = 100$$

Subject to:

1) Distance constraints: $\left\| x(q)^{end-effector} - x^{target\ point} \right\| \le \varepsilon$
2) Joint limits: $q_i^L \le q_i \le q_i^U; i = 1,2,\ldots,DOF$
3) Torque limits: $\tau_i^L \le \tau_i \le \tau_i^U; i = 1,2,\ldots,DOF$
4) All contact points on contact plane:
   $(n_{ground} \cdot (x_c^{support}(q) - p_{ground}))^2 \le \varepsilon; c = 1,2,3,4$
   where $x_c^{support}$ represents a local contact point on the foot.
5) ZMP restricted to be inside the foot support area (FSR):
   $(P_{zmp} - P_i(q)) \times (P_{i+1}(q) - P_i(q)) \cdot n \le \varepsilon; i = 1,2,3,4; P_5 = P_1;$
   where P_i is a local foot boundary position.

Static equilibrium, including reaction forces and calculation of the zero-moment-point (ZMP), is inherently considered in the calculation of joint torques, which is conducted using a variation of the method discussed by Kim *et al* (2008). The aforementioned method has been adapted to the static case and thus only considers torques due to gravity and defined external forces. Essentially, equations of static equilibrium are included as constraints. Then, a ZMP constraint is implemented to ensure the avatar remains balanced. The ZMP is comparable to the center of gravity but with consideration of external forces, not just gravity (Vukobratovic and Borovac, 2004). This point is constrained to remain within a foot support region. The predicted joint-torques are constrained to remain within limits representing strength restrictions.

The objective function used to combine torques was developed by Marler (2005) as an approximation of the min-max approach to multi-objective optimization. Thus, the maximum joint-torque in the body is minimized. With smaller values of p, this function tends to mimic a sum, resulting in the collective minimization of all torques.

3 Results

As an initial test of the calculated torques, Santos was positioned with his arm extended forward. While considering the weight of the arm and hand, the predicted torque was 11.84Nm. The torque calculated analytically was approximately the same: 12.01Nm.

As a more functional basic test, posture is predicted with a 40N upward force applied to each wrist (Figure 2), with the global DOFs fixed. The feet are constrained to the ground, but their precise position is predicted. The torque objective function is combined with a joint displacement function (Marler *et al*, 2009), using the formulation developed by Marler (2005) and using weights of 0.75 (75%) and 0.25 (25%), respectively. The predicted posture is reasonable and results in low joint torques throughout the body. Furthermore all predicted joint torques are well within literature-based limits.

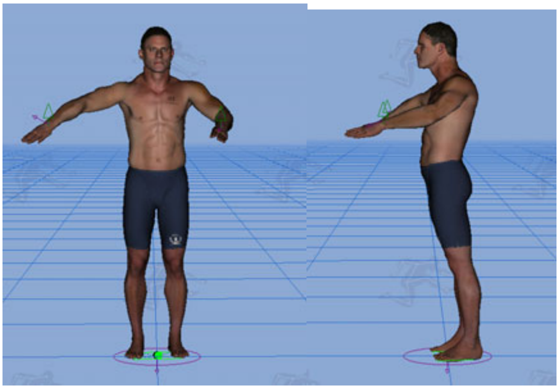

Fig. 2. Basic Test with Upward Forces

Figure 3 shows a series of tests with downward forces. When joint displacement is used alone, although most joint torques are relatively low, the torque in the right clavicle joint is nearly at its limit, indicating excessive use of the upper back muscles. With the second case, joint displacement is combined with maximum torque, which acts to reduce the clavicle torque. However, the load is distributed to the spine (lower back) where the risk of injury can be high. The third case provides a balance between using upper and lower back muscles. This series of tests demonstrates how different objective functions can be used to study what drives human behavior. Although joint torque (and associated muscle force) plays a significant role, it is not the only factor. In general, we find that minimizing maximum joint torque (as opposed to a sum of joint torques) provides the most realistic results, a finding that corresponds well with experimental findings in the literature (Zacher and Bubb, 2004). However, in some cases (i.e. Figure 3) humans behave based on slightly different objectives, and the presented model allows for this versatility. In the vein, the proposed work can be used for trade-off analyses to study what kinds of postures tend to minimize which performance measures.

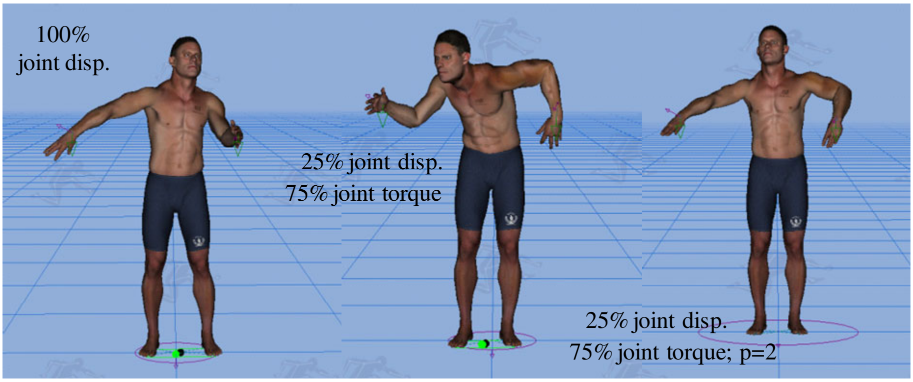

Fig. 3. Basic Tests with Downward Forces

The proposed approach is now applied to a basic box-lifting task with a box of dimensions 55cm X 39cm X 32 cm. Whole-body posture and foot position are predicted while respecting the ZMP constraint. Figure 4 shows predicted results with a weightless box and a 20lb box, and then motion capture results. The posture while considering the weight of the box involves slightly more bending of the knees and a straighter back. The motion capture results show a slight bend in the arm, which is a result of the anticipated motion that would require the box avoiding the knees as the box is lifted. The posture prediction results model the approximate case of pulling up on a static box, rather than initiating motion. Nonetheless, although posture prediction provides an approximate simulation of box lifting tasks, its computational speed (typically less than fifteen seconds with external forces) and versatility provide a useful tool.

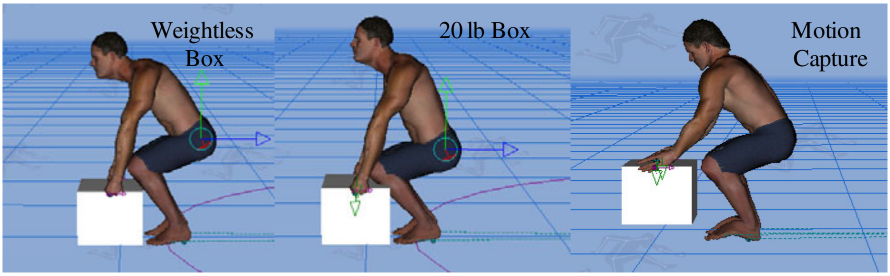

Fig. 4. Box Lifting Results with 25% Joint Displacement and 75% Joint Torque

Figure 5 shows results using a female avatar with an alternate combination of performance measures. Clearly, box lifting tasks require one to focus on minimizing joint torque rather than joint displacement. When more joint displacement is included in the objective function, relatively high joint torques arise in the hip. Thus, typical strategies in lifting boxes help reduce hip torque as well as back torques.

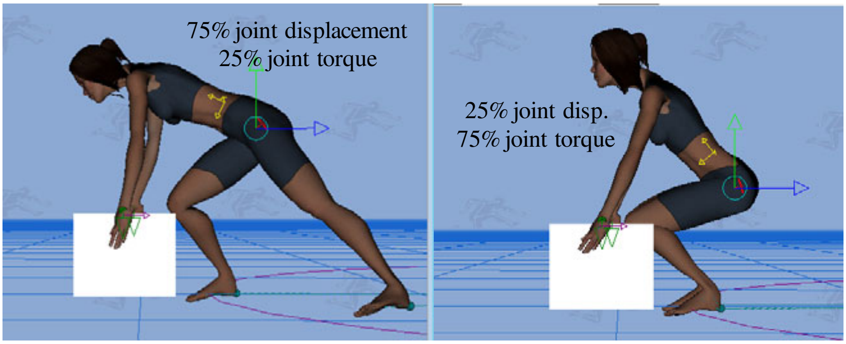

Fig. 5. Box Lifting Results with Alternate Performance Measures

4 Discussion

This paper has presented new capabilities for optimization-based posture prediction with external forces. A computationally fast and robust method has been presented for predicting human whole-body postures while considering any set of external forces or torques, as well as balance. Not only is the posture predicted in near real time but so is the overall body position and orientation. Although applied to a box lifting task for his work, the proposed method can be used with infinitely many scenarios. Furthermore, this optimization-based approach allows one to study what drives human performance.

During this study, a few interesting issues surfaced. When compared to motion-capture results, the distinction between box-lifting motion and simply touching or pulling on a box surfaces. Posture prediction or even quasi-static analysis does not consider path planning (future conditions at each time step). Using posture prediction for a box lifting task provides only an approximation of the visual results. Nonetheless, it is useful for studying trends in joint torque and thus the propensity for injury. Secondly, with some of the results, there was a slight intersection between the box and the avatar knees. Collision avoidance is incorporated in this study, but the surrogate geometry used to represent the box is approximate and needs to be refined.

With an optimization-based approach, one often raises the question of which objective function to use. However, the objective functions not only provide means of modeling and simulating human performance, but also tools in virtual experiments, to see the consequences of different drivers.

Acknowledgments. The authors would like to thank Mr. John Meusch for his support and input.

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