SANTOS: A PHYSICS-BASED DIGITAL HUMAN SIMULATION ENVIRONMENT

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This paper presents a comprehensive human modeling and simulation environment under development by the University of Iowa Virtual Soldier Research (VSR) program. This environment, called Santos™, is a new generation of digital human simulation systems that allows for a user to interact with a digital character with full and accurate biomechanics and a complete muscular system, subject to the laws of physics. Highlighting major results in the areas of dynamic motion prediction, modeling of clothing, modeling of muscle activation and loading, and the Santos intuitive interface will be presented. This paper will feature the various modules that comprise the Santos environment.

INTRODUCTION

The use of digital humans has gained momentum in product design, manufacturing assembly lines, maintenance, and the military. Digital humans can be used to embed real-time representations of live participants in virtual environments. There has been considerable research in this area, and several commercial software programs are available, including Jack, Safework, and RAMSIS. Despite their impressive capabilities, however, the software programs can't explain why humans move as they do. Our objective is to investigate that question and develop a digital human model known as Santos™.

Santos is a digital human model characterized by a complete musculoskeletal model. He is a "typical human" capable of accomplishing tasks unaided. Because he is built on a sound physics and physiology foundation, we can monitor his progress during a task both visually and by monitoring his vitals. This paper describes the human model, real-time dynamics, physiology model, clothing modeling, skeletal muscle modeling and simulation, and muscle wrapping and force determination.

HUMAN MODEL

The human body can be modeled as a kinematic system, a series of links connected by rotational degrees of freedom (DOF) that collectively represent musculoskeletal joints such as the wrist, elbow, vertebra, or shoulder. In this section, the basic skeleton of the model is described in terms of kinematics. In this sense, a human body is essentially a series of links connected by kinematic revolute joints. Each DOF corresponds to one kinematic revolute joint, and these revolute joints can be combined to model various musculoskeletal joints. In order to better represent human motion, a 109-DOF model for the human body has been developed.

Figure 1 illustrates Santos with the kinematic model (skeleton). The DH method (Denavit and Hartenberg, 1955) provides a matrix notation and approach for relating the position of a point in one coordinate system to a point in another coordinate system by using a unique transformation matrix.

REAL-TIME DYNAMICS

Although dynamic analysis is a broad and well-developed field, we are developing a new method called *predictive dynamics*, which is especially well-suited for simulating human motion. Predictive dynamics uses optimization to provide both forces and kinematics data simultaneously.

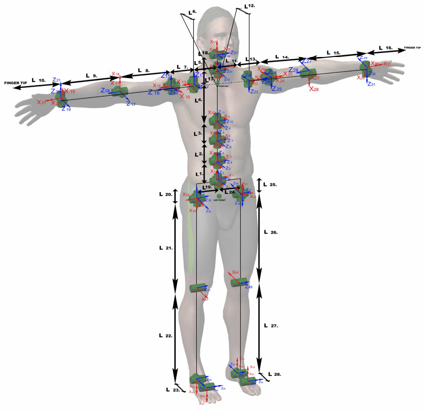

Figure 1 Santos model

To develop predictive dynamics, our optimization-based approach for kinematics motion prediction is augmented by including the equations of motion as constraints. In this way, cumbersome and time-consuming integration is not necessary. This approach avoids using typical forward dynamics to solve equations of motion, easily accommodates highly complex human models, incorporates externally applied loads, and potentially functions in real-time.

Our approach to kinematics motion prediction, which forms the basis for dynamic motion prediction, is described as follows. Conceptually, the design variables for the optimization problem are time-histories for the joint angles (plots of a joint angle versus time). In order to facilitate actual numerical optimization, these curves are represented with B-splines, and technically the B-spline parameters provide the design variables. The objective functions (to be minimized) represent *physics-based* performance measures, which are metrics that govern how people move. The primary constraints require the joint angles to remain within specified limits. In addition, various points in the body are constrained to contact specified points in space contingent on the task being completed.

We have devised a way to modify this approach so that dynamic analysis can be incorporated. Essentially, the equations of motion are derived using Lagrangian dynamics and are incorporated as additional constraints. Thus, the equations of motion are automatically satisfied without numerical integration. Then, given externally applied loads, not only are time-histories for joint angles calculated, so are torques at the joints.

The structure for this environment is shown in Figure 2. At the core of this environment are general-purpose modules that can be used to study various dynamics activities. These consist of the optimization module, the B-spline module, the DH module, the inverse dynamics module, the cost function modules, and the constraint modules. Using these modules, a variety of tasks, such as walking, can be modeled by modifying the performance measure(s) and constraints. In fact, this is the foundation for what we call *task-based motion prediction*, which suggests that what motivates human motion depends on the task being completed.

Using predictive dynamics, we have devised a new physics-based approach for modeling gait and balance that does not require prerecorded data. The process of taking a step is decomposed as shown in Figure 3. The process of walking is then decomposed into different steps (Figure 4), which are then simulated with separate optimization problems. In the case of walking, the performance measure is the total required joint torque throughout the body. There are five types of constraints for this task: joint limits as discussed above, torque limits for each joint, restricting feet from penetrating the ground, zero moment point (ZMP), and the specification of a series of foot-strike points.

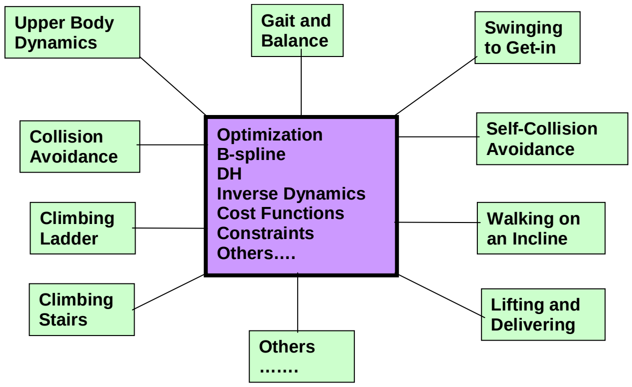

Figure 2 Structure of dynamics simulation

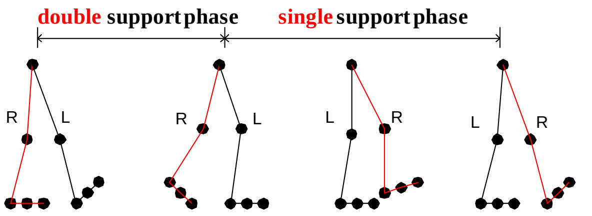

Figure 3 Two phases in a step (R: right leg, L: left leg)

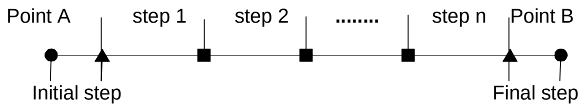

Figure 4 Long-distance walking

PHYSIOLOGY MODEL

The human body requires energy to conduct its various activities. The energy is derived from energy substrates within the body, such as fats and carbohydrates. By utilizing mathematical relationships between the energy produced and the heart rate and oxygen consumed, it is possible to derive physiological indices such as the heart rate, ventilation rate, carbon-dioxide production rate, and rectal temperature.

(1) Oxygen Uptake: In the Santos model, the oxygen uptake is assumed to produce all of the aerobic energy requirements. Initially, most of the energy produced is anaerobic, and over time the aerobic component increases until almost all the energy required is produced aerobically. The rise of the oxygen uptake can be described as a mono-exponential function (Barstow and Mole, 1991) reaching a steady state within 3-5 minutes.. The oxygen uptake is found to be dependent on time and energy requirements.

(2) Heart Rate: Once the oxygen uptake has been determined it is then possible to determine the heart rate using Fick's equation, which is essentially a mass balance equation. The increased levels of oxygen required by the body have to be delivered by the circulating blood. In order to do this, the heart increases its arteriovenous oxygen difference, stroke volume, and finally the number of beats per minute. All of these factors have a direct relationship with the oxygen uptake (Margaria, 1976; Margaria et al., 1970; Barstow and Mole, 1987).

(3) Breathing Rate: Pulmonary ventilation (the volume of air taken in a single breath) and breathing frequency (breathing rate) are more closely related to the carbon dioxide (CO_2), produced as an end product of energy creation (Wasserman et al., 1967) than to the oxygen required for energy production. The body needs to regulate its pH levels in the blood, which are lowered due to the presence of acidic CO_2. It does so by bicarbonate buffering. The end product is CO_2 and needs to be released, which is done by increasing the ventilation rate. Predicting the breathing frequency is more complex as individuals set their own breathing rate by a mechanism which has yet to be understood. Based on a study conducted by Neder et al., (2003), a trend line was plotted, yielding a relationship between breathing frequency and ventilation rate.

(4) Rectal Temperature: The rectal temperature is the closest measure of core body temperature. Formulas based on a biophysical model have been developed previously in literature and predict the time response pattern of rectal temperature response to work, environmental, and clothing condition properties. Three separate formulas are required for the patterns of change in rectal temperature—one during rest in the heat, another to mimic the rise during work, and a third for recovery after cessation of work. The formulas involve the metabolic heat production, the ambient climatic conditions, and the total thermal resistance and evaporative coefficient of the clothing (Givoni and Goldman, 1972; Givoni and Goldman, 1973).

(5) Physiological Strain Index: The Physiological Strain Index (PSI) is an index designed to analyze the strain on the body due to the work rate and exposure to the environment. It is a function of the heart rate and the rectal temperature. The heart rate is a function of the metabolic energy production rate, and the rectal temperature is a function of the metabolic energy production as well as the environment. The PSI rates the physiological strain on a universal scale from 0-10. It can be effectively used for a normothermia (normal core temperature) value of 36.5^o C to a hyperthermia (higher bound of core temperature) value of 39.5^o C. The range of the heart rate values is 60 beats/min at rest to 180 beats/min at the maximum workload. This is the prescribed range to limit the scale to values between 0-10 (Moran et al., 1998).

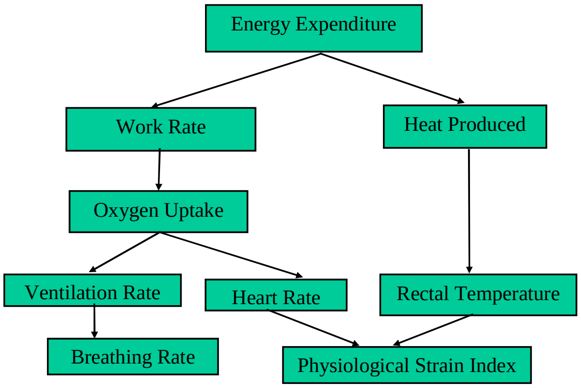

Figure 5 The process flow for the Santos physiology module

CLOTHING MODELING

In the analysis and design of military uniforms and body armor systems it is helpful to quantify the effects of the clothing/armor system on a wearer's physical performance capabilities. Toward this end, a clothing modeling framework for quantifying the mechanical interactions between a given uniform or body armor system design and a specific wearer performing defined physical tasks has been implemented. The macroscopic fabric model is based on a rigorous large deformation continuum-degenerated shell theory representation within an implicit-explicit finite element framework. The homogenized effective constitutive behaviors of fabrics are obtained by usage of micro-scale unit cell models. The collision and contact module enforces non-penetration constraints between the fabric and human body and computes the associated contact forces between the two. The human body is represented in the current framework, as an assemblage of overlapping ellipsoids that undergo rigid body motions consistent with human motions while performing actions such as walking, running, or jumping. The transient rigid body motions of each ellipsoidal body segment in time are determined using motion capture technology. The integrated modeling framework is then exercised to quantify the resistance that the clothing exerts on the wearer during the specific activities under consideration.

One example is illustrated. A human subject walks four strides, with the third involving stepping over an obstacle 0.5m in height. The motion of this human is captured with an array of eight infrared Vicon cameras, and the motions are then mapped onto the assemblage of ellipsoids to make them walk. A pair of pants is then placed onto the human model (Fig. 6) in the following sequence: (a) the feet of the human model are removed; (b) the pants of are pulled up over the legs and pelvis; (c) the feet of the human model are then restored; and (d) the effect of a belt is created by tensioning the fabric at the waistline. With the garment on the human model, a simulation of the interaction between the pants and the walking lower body walking and crossing the obstacle is then undertaken (Fig. 7).

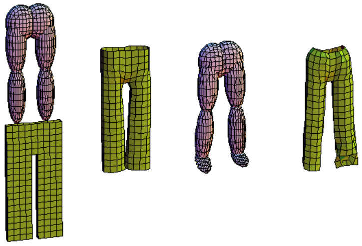

Figure 6 Sequence for the human model to don a pair of pants

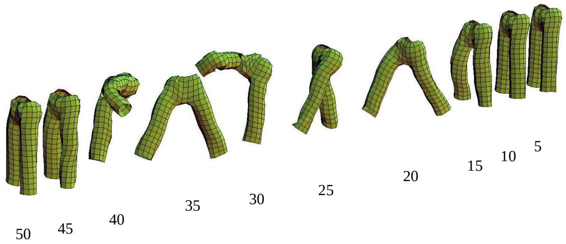

Figure 7 Simulation of pants interacting with lower body striding and then stepping over an obstacle.

MUSCLE MODELING

We are working on incorporating representations of skeletal muscle at several perspectives—individual muscles as well as the joint space level. In general, in vivo muscle force is a highly nonlinear phenomenon that is dependent on factors such as muscle length, velocity of contraction, and past contractile history (e.g., fatigue and potentiation). Despite these known nonlinearities, muscle force has been adequately modeled as a linear system of springs, dampers, and viscoelastic components (Epstein and Herzog, 1998). This approach is currently best suited to modeling a small subset of the human body, as the entire body is an over-determined system. Thus, to produce a given set of joint torques, numerous combinations of muscle activation strategies may be used.

Many mathematical representations of human strength have been restricted to static or quasi-static assessments. However, we know that with dynamic motions, muscle-force-producing capability decreases in a curvilinear manner with increasing shortening velocity (Lieber, 1992). This relationship, first described in 1938 by Hill, is known as the muscle force–velocity relationship (Hill, 1938). It can be extended to joint space as the torque–angular velocity relationship, where with increasing shortening angular velocity, the ability to generate torque decreases. This may be commonly understood as the fact that heavier items are more difficult to lift quickly; ultimately a load may be so great as no joint angular velocity may be generated at all (an isometric contraction).

Additionally, isolated muscle force capability is dependent on the length of a muscle. At the shortest lengths, there is believed to be an inefficient overlap of the actin and myosin filaments, resulting in lower than optimal force production. At the longest muscle lengths, the filaments have little overlap, also compromising force production. Thus, there appears to be an ‘ideal region’ where the actin and myosin filaments overlap optimally to produce muscle force. In joint space, this relationship is further complicated by changes in functional muscle moment arm lengths. Experimental measurements in human subjects have demonstrated these changes in maximal joint torque production at varying joint angles (Lieber, 1992).

Using these two basic muscle physiology concepts, consistently demonstrated in both isolated animal preparations and in functional human studies, we will compare predicted major joint torques to normative data, considering both velocity and position. By plotting the joint torque relative to joint angular position and velocity, we can assess how near to maximum capability a given task would be. The closer to maximum, the more relatively difficult, if not impossible, a task becomes. This provides a unique methodology for a digital human to predict the perceived level of difficulty of a subtask.

Figure 8 shows elbow flexion torque-velocity data obtained from the literature (Griffin et al., 1993; Colson et al., 1999; Mikesky et al., 1995; Pousson et al., 2001; Pousson et al., 1999; Housh and Housh, 1993; Hortobagyi and Katch, 1990; Shepstone et al., 2005; Sale et al., 1987; Vandervoort et al., 1987; Gallagher et al., 1997; Knapik and Ramos, 1980; Ellenbecker and Roetert, 2003), and two predicted Santos torque-velocity profiles. The predicted tasks were performing a simple biceps curl exercise using 250 N versus 10 N. This example demonstrates that to lift a 250 N load (~ 56 lbs) with one hand would be beyond the strength capability in nearly one-half of the reported studies even at a very slow rate. The 10 N exercise clearly could be performed by all subjects and could be performed more quickly before approaching the average maximum torque-velocity line.

Lastly, as muscles fatigue, both maximum torque and velocity are impacted, i.e., it becomes increasingly more difficult to generate large joint torques and high movement velocities. This assessment approach, using torque-velocity to assess dynamic muscle strength, may also serve to represent fatigue via a decay function to reduce the torque – velocity curves. As tasks require repetitive or prolonged joint torque, the maximal ability of the joints will decay.

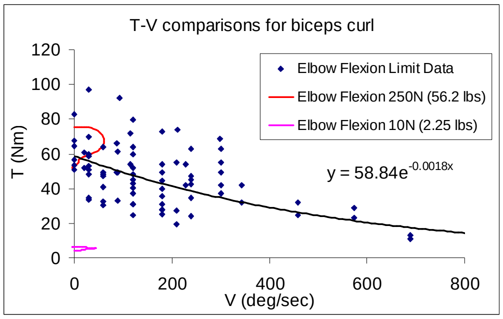

Figure 8 Summary of maximum elbow flexion torque-velocity data obtained from a comprehensive literature review

MUSCLE WRAPPING AND FORCES

Muscle wrapping is incorporated into the musculoskeletal model by assigning one or more wrapping algorithms we have developed to an action line. After determining the insertion and origin points of all the muscles, as well as the position of the related wrapping obstacles the resulting 3D model is shown in Figure 9. Additionally, the simulation was programmed to allow the user complete real-time interaction with any of the joints in the kinematic chain. Some of the results of wrapping at the elbow can be seen in Figure 9.

Figure 9 Movement and wrapping about the shoulder

When resolving a joint torque into individual muscle forces, one must develop a method that can solve the indeterminate problem presented by multiple muscles contributing to a single joint torque. A quick review of the literature will reveal that prediction of muscle force or activation has been studied at length (Seireg and Avikar, 1973; Pedotti et al., 1978; Crowninshield and Brand, 1981; Kaufman et al., 1991; Happee, 1994; Glitsch and Baumann, 1997; Anderson and Pandy, 1999; Chadwick and Nicol, 2000; Praagman et al., 2006). These approaches have ranged from simple formulations such as sharing the load based on muscle stress (Amis et al., 1980) to extensive dynamic optimization algorithms (Davy and Audu, 1987).

Solving this problem with optimization requires a cost function that will be minimized while obeying various constraints. For very strenuous activities, Crowninshield found that minimizing the sum of the muscle stresses while imposing constraints on how high the stresses can become resulted in data that correlated well with EMG signals (Crowninshield, 1978). Pedotti et al. (1978) minimized Eq. (1) where $f_{\max}$ was calculated from instantaneous muscle length and muscle velocity of the shortening and found a correlation with muscles associated with human gait.

$$U = \sum \left(\frac{f_i}{f_{\max_i}} \right)^2 \tag{1}$$

One way this problem can be solved is with the following optimization formulation where a_i is the activation level of the i^{th} muscle and n is the number of muscles being considered. Note that this formulation is similar to Eq. (1).

Design Variables: $a_1, \ldots, a_n$

Minimize: $J = \sum_{i=1}^{n} a_i^2$

Subject To: $\bar{T} = \sum_{i=1}^{n} \bar{r}_i \times a_i \bar{F}_{\max_i}$

$$0 \le a_i \le 1$$

Note that by simply adding more torque equation constraints this formulation can be expanded to cover numerous joints. It should be emphasized that our motivation is not to determine which formulation is the best but simply to create a real-time model that can work with many different formulations so that users can determine which formulations they prefer for specific tasks.

CONCLUSION

This paper has presented a physics-based digital human. It boasts 109 degrees of freedom and accurate modeling of the human musculoskeletal system. Our truly multi-disciplinary results have yielded a novel method for performing dynamics without the use of integrators, but rather using optimization techniques. A real-time dynamics platform has been built to obtain task-based dynamic prediction such as walking, running, swinging, etc. Physiology model has been investigated. Accurate physics-based modeling of clothing is the first step in studying body and clothing interaction. Muscle modeling and force determination will be benefit for muscle fatigue analysis and biomechanical study.

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