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Human motion analysis for biomechanics and biomedicine

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1 Introduction

The study of human locomotion can be described as the interdiscipline that describes, analyzes, and assesses human movement. This endeavor represents an important branch of bioscience that requires a multidisciplinary effort and has immense potential to aid mankind.

The applications of human motion analysis are limitless. Researchers in the fields of biomechanics, medicine, sports, and rehabilitation study human locomotion for evaluating joint forces and moments that control motion and posture [7,18,25]. Such studies are fundamental to understanding the mechanics of normal and pathological movement [11,29], and for the diagnosis and treatment of patients with motor deficiencies [28]. Synthetic humans may be used to test strategies to optimize various sport movements or to animate enhanced visualization of the human form to aid in clinical analysis [4,10]. Simulation allows a physician to observe which muscles are being activated during certain movements in order to design correctional devices that can ease joint loads caused by injury. Others in the field of biomedicine use human models for the development of functional electrical stimulation (FES) protocols to restore mobility to paralyzed individuals [3,8,9,32].

In animation and computer graphics, human motion analysis is important to animators who wish to generate physically-based animations of synthetic humanoids [2,23,24], allowing the physical effects of movement to be automatically generated as a byproduct of the simulation [6,15,19,30].

In the manufacturing industry, digital humans are being used as virtual operators acting within simulated environments, manufacturing automotive components, assembling aircrafts, and maintaining next-generation power plants and nuclear submarines [21]. Humanoid robots and human exoskeletons can benefit from studies of human motion. Understanding human motion has been instrumental in developing tools for simulation and control of biped robots [1,12–14,16,17,24,26].

In computer vision, human motion analysis has emerged as an important area of research, motivated by the desire for improved man–machine interfaces. In particular, the ability to recognize human activity by visual information processing is instrumental to making a machine interact purposefully and effortlessly within a human-inhabited environment [22,31]. Other areas that have recently received considerable attention due to security concerns include surveillance.

Clearly, human motion analysis and synthesis has widespread applications spanning many disciplines. The important research questions require a unified, multidisciplinary solution that utilize theories developed in human motor control, robotics, muscle mechanics, computer graphics, and computer vision.

2 Human motion analysis: a unified approach

At Honda Research Institute USA, we are pursuing a unified approach to resolve many of the interdisciplinary problems associated with the analysis and synthesis of human motion. Although our current focus areas include biomechanics and biomedicine, the framework is general and may be beneficial for other applications.

The original concept of the proposed framework can be understood by considering a simplified illustration of how the human neuromuscular system controls its motion (see Fig. 1).

Motion planning is initiated in the central nervous system (CNS). The sensorimotor control system in our brain generates a sequence of neural activations that innervate the muscles, causing them to contract and generate the forces required to drive the skeletal system to a desired position. Sensory infor-

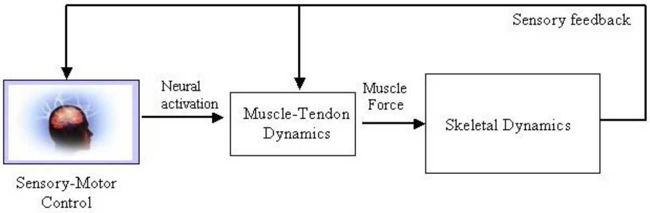

Fig. 1. Simplified depiction of the human neuromusculoskeletal system

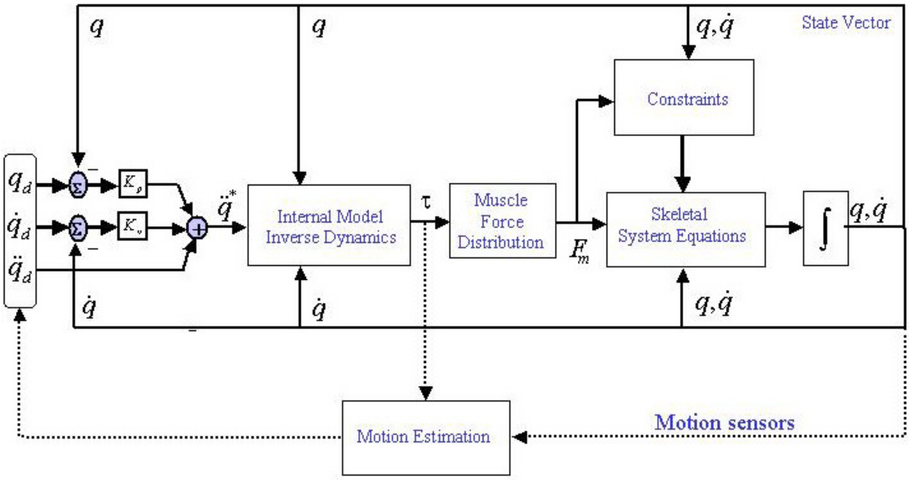

Fig. 2. Realizable architecture for analysis and synthesis of human motion. The state vector, joint torques, and muscle forces are denoted by $[q, \dot{q}]$, τ, and F_m, respectively

mation such as muscle length, and skeleton motion parameters are fed back to the sensorimotor control and the skeletal muscles.

3 Realization of a unified approach

The approach we adopt to develop a computational model of human sensorimotor control is based on the concept of an internal inverse dynamics model coupled with nonlinear feedback (Fig. 2). This approach represents a realization of the scenario outlined in Fig. 1. In this model, the desired kinematics (denoted by q_d) are assumed to be available from sensors. More details on motion sensing is described in the next section.

The kinematics are differentiated twice to determine the velocities ($\dot{q}_d$) and accelerations ($\ddot{q}_d$). These reference signals are applied to an error-correction controller with proportional and velocity feedback gains (K_p and K_v). The error-corrected acceleration vector ($\ddot{q}^*$) is used as an input to an inverse dynamics module. The output of the inverse dynamics module represents the joint torques, denoted by τ. The use of an inverse dynamics model as the "internal model" for the CNS to control motion has been proposed in the past. The concept of an inverse dynamics model is also attractive for analysis problems of biomechanical quantities, whereby internal loads are estimated from kinesiological measurements.

In humans, the net joint torques (τ) are relegated to several muscles spanning the joint. This redundancy can be resolved by performing static or dynamic optimization in a block referred to as the *muscle force distribution*. The computed muscle forces (F_m) serve as the inputs to the forward dynamics block. Effectively, forward simulations represent the synthesis of human motion. In addition, the forces of contact are computed in the constraints module. The mechanism in Fig. 2 is compelling from the standpoint of biomechanical analysis and synthesis of human motion.

4 Motion planning

There are two approaches in addressing motion planning: computational vs. experimental.

4.1 Optimal control-based planning

The computational approach relies on modeling the neuromusculoskeletal system and prediction of motion through analytical formulations such as optimization or optimal control. In order for such methods to generate physically correct and natural-looking human motion, they require realistic models of the musculoskeletal system and control strategies that mimic the way the central nervous system (CNS) controls its motion. Potentially, optimal control theory is the most powerful method for realizing human motion, provided that the selected performance criterion is the same as the one used in biological systems. This method delivers a purely predictive result, independent of experiment, and allows muscle dynamics to be included in the problem formulation. Numerous models have been developed that give insight into the organization of movement control in the nervous system, which is the method by which the optimal trajectory is formed. Critics of these approaches argue that uniqueness of a performance criterion can neither be guaranteed nor proven. Ultimately, the performance measure is hypothesized, and the computed optimal control solution is compared with experimental data to support, reject, or refine the assumed performance criterion. Practically speaking, issues concerning computational costs, convergence, and stability associated with nonlinear optimization of large-scale systems are unresolved.

4.2 Motion capture

Motion capture is an alternative, experimental method for bypassing kinematic redundancies involved in the execution of a motion task. In motion capture, the method for measuring human movement involves placing markers or fixtures on the skin surface of the segment(s) being analyzed. The observation and analysis of human motion from captured video is instrumental to a large number of activities and applications such as security, character animation, virtual reality, human–machine interfaces, camera control, and traffic and customer monitoring.

4.3 Markerless and nonrigid tracking

An application of human motion estimation that has been overlooked by the computer vision community is biomechanics and biomedicine. It is important to understand that the most basic assumption made to analyze human motion is that body segments can be modeled as rigid bodies. That is, the position and motion of the underlying skeleton can be approximated by tracking the position and motion of the surface tissue. The underlying error in this assumption is referred to as *soft-tissue motion error*, which is inherent in all motion analysis of human subjects using markers. Skin movement relative to the underlying bone is the most important factor limiting the resolution of detailed joint movement using motion capture and other skin-based systems. The clinical relevance of human motion would be substantially improved if reliable measurement of skeletal movement could be obtained from skin-based marker systems.

Very few research tests have been conducted to evaluate the amount of error resulting from soft-tissue movement. These tests have involved invasive techniques of putting pins in the bones and attaching markers to those pins and comparing pin marker movement with that of surface markers. Therefore, it is important to place surface markers at points where soft-tissue movement is a minimum. Obviously, this can present problems when testing individuals who are obese. The next generation vision system must offer alternative ways to study human motion by avoiding the intrusive markers that not only encumber movement, but also are unreliable in many biomechanical applications.

Recently, new approaches have been developed that have the potential to address the nonrigid body movement of the limb segment. Some of these approaches are marker based and involve using a cluster of markers at a joint. More recently, markerless motion estimation for 3D nonrigid tracking has been introduced [27]. The lack of prominent features to track substantially limits widespread use of such techniques.

4.4 Ubiquitous sensing

The challenges for accurate, non-intrusive estimation of human motion are tremendous. However, there are facilities within several institutions which are well equipped to begin this type of research. Two such facilities include the Keck Lab at the University of Maryland and the 3D Room at Carnegie Mellon University. In these laboratories, it is possible to capture and model a 3D event varying in real time, such as human motion, with a computer. A large number of cameras are mounted in a room, all of which are synchronized with a common signal. The video signals are simultaneously digitized in real time. Such facilities may open the door to precise reconstruction of human activities without the use of external markers. The ubiquitous-sensing group at Honda is developing "3D Life," a project focusing on alternative approaches to achieving high-resolution 3D motion and structure of humans from a large set of sensors.

It is important to note that the requirements for human motion estimation in biomechanical and medical applications are much more rigorous than most other applications, such as entertainment and security. To be useful in clinical applications, the 3D joint locations must be estimated with high precision. This task would require not only vision research in the 3D reconstruction and tracking, but also geometric modeling and computer graphics tools for registration of the reconstructed surfaces to precise joint positions.

5 Closing the loop

It is clear that visual sensing is an integral element in closing the loop for dynamic, musculoskeletal modeling and the simulation of humans (see Fig. 2). The extended Kalman filter (EKF) has previously been used in computer vision for the estimation of object motion parameters from a sequence of noisy images [5,20]. Kalman filters provide the optimal estimate for dynamic systems, and they are based on physical dynamics, which allows for predictive estimation. Methods using state estimation and prediction, such as Kalman filters, do not consider the active inputs (or controls) that drive the dynamic system. It may be appropriate to include observations from the joint torques in the state estimation as illustrated in Fig. 2.

6 Summary

Human motion analysis and synthesis is an interdisciplinary problem with application spanning areas such as biomedicine, biomechanics, human-figure animation, ergonomics, and machine vision. A great deal of effort must be directed toward developing and implementing methods whereby the specific problems in sensing, modeling, control, and simulation are conducted in a unified approach.

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