

Task-Level Reconstruction and Analysis of Dynamic Motions in Human Musculoskeletal Systems

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Abstract— Understanding human motor control involves studying the principles used to optimize dynamic movement. This process requires accurate modeling and simulation of musculoskeletal kinematics, reconstruction of motion dynamics, and characterization of elite performance motor skills. Motivated by the previous robotics research applied to these challenges, the present research aims to leverage the task-level control strategies to reconstruct and analyze human dynamic motions, introducing the approaches of (i) modeling of human musculoskeletal system for task-level motion control, (ii) task-level reconstruction of human motion, (iii) robotics-based analysis of human dynamic skills. Our findings suggest that task-based control approach is an attractive tool to reconstruct and analyze the dynamic motions of human and other complex articulated body systems in a computationally efficient manner.

I. INTRODUCTION

ROBOTICS-BASED approach of exploring natural human skills provides generalized motion analysis techniques and physiologically accurate performance predictions applicable in the domains of sport medicine, rehabilitation and physical therapy.

II. MODELING OF HUMAN MUSCULOSKELETAL SYSTEM

The full body musculoskeletal model was derived from upper and lower musculoskeletal models [3, 7] and includes 177 degrees of freedom and 323 muscles (Fig. 1). The full body model was scaled based on body segment mass-center locations [15] to match the anthropometry of the subject. Figure 1 illustrates the scaled musculoskeletal model used in our control and simulation framework and Figure 2 shows the body segments of the model, each connected to its parent body via the corresponding custom joint. For example, the right ulna is connected to its parent body, right humerus via the right elbow custom joint. Note that the Figure 2 shows the tree-like branching structure of the simplified generic human model that we use in our control framework.

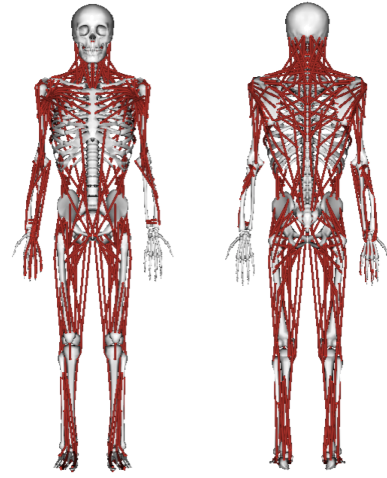


Fig. 1. Human Full-body Musculoskeletal Model including 177 degrees of freedom and 323 muscles (created in [3] using [7, 8]).

III. HUMAN MOTION RECONSTRUCTION

Human motion reconstruction requires predicting the dynamics as the motion is being executed. In order to fully describe the characteristics involved in human skills, one needs to map the motion sensing to physio-mechanically correct subject-specific human models. Recently, we demonstrated that the task-based control approach can efficiently reconstruct a subject's motion dynamics in real world task-space when given a scaled model and marker

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based motion capture data. Our marker space reconstruction methodology provides the full motion dynamics by operating in marker space and automatically resolving the kinematic constraints of the markers [4, 5].

Robotics-based motion reconstruction was achieved by producing the subject's full body dynamics through the operational space control [1] of a simulated human musculoskeletal model [4, 5] to track the captured marker trajectories in real-time. Here, we introduced the whole-body control formulation and hierarchy in marker space where we tracked the positions, velocities, and accelerations of many markers in parallel by assigning them to tasks with different priority levels based on how free their parent limb was. We executed lower priority marker tracking tasks in the successive null spaces of the higher priority tasks to resolve their dependencies.

The implementation of the marker space control formulation [4], to the human model requires building a hierarchy of independent marker sets. Our approach for assigning markers to these task-sets is based on the observation that two markers can be controlled independently if they are separated by three degrees of freedom that span the space of motion. This principle is applied to the human model following its natural tree-like branching structure (Fig. 2). The first level in the task hierarchy is formed by markers placed on the pelvis, its root, and on the hands and feet, its leaves. The following levels are constructed with markers placed on the intermediate links through assignments consistent with the above principle. Additional tasks, such as postures and dissipative forces, are included in the lowest level of the hierarchy.

Human motion reconstruction algorithm [4, 5] was implemented and tested on many various dynamic motions including tai-chi motion sequences, dance performance and

football throwing. Overall, the results show that fast dynamic motions can be effectively reconstructed in near real-time and with little error (2-4cm) even for fast dynamic motions.

IV. ROBOTICS-BASED ANALYSIS OF HUMAN SKILLS

The development of the human motion reconstruction algorithm explained in the previous section draws upon an advanced musculoskeletal modeling platform and a task-oriented control framework leading to the effective integration of biomechanics and robotics methods. This control and simulation framework provides us the motion dynamics that is used for the robotics-based analysis of human skills.

Recently, we established that robotics-based analysis of human motion can be applied to explore the characteristics that shape the natural human motion [6]. Task-driven human performance metrics, including the acceleration-based effort expenditure criteria and muscular effort minimization criteria were developed and tested for goal-oriented human skills. These criteria correlated to the observed motion characteristics including the musculoskeletal physiology, kinematic and dynamic parameters.

The characterization of effort expenditure in terms of both skeletal parameters and the muscle physiology is based on a task-based muscle effort measure, specifically,

$$E = F^T \left[J \left(L^T N_c^2 L \right)^{-1} J^T \right] F \quad (1)$$

where N_c is the $r \times r$ muscle capacity matrix and L is the $r \times n$ muscle Jacobian matrix (moment arms) for a system of n joints and r muscles.

In Equation (1), the term in bracket connects the muscle physiology to the operational space force, F , through the Jacobian, J .

Robotics-based analysis of human motion includes also the characterization of operational space accelerations for a given task. The analysis of the operational space accelerations is motivated by the successful extension of operational space control to analyze the dynamic performance of robotic systems [8]. In this framework, the idea is to map the analysis of bounds on joint torques to the resulting end-effector accelerations in the workspace of the manipulator. Similar model can be applied to characterize and analyze human dynamic skills shaped by the skeletal mechanics as well as the physiological parameters.

For this system of n equations and r muscles, Γ is the $r \times r$ vector of muscle induced joint torques and A is the $n \times n$ mass matrix. Using the operational space acceleration & muscle force relationship

$$\ddot{x} = J(q)A(q)^{-1}(\Gamma - g(q)) \quad (2)$$

where $g(q)$ is the $r \times 1$ gravity torque vector.

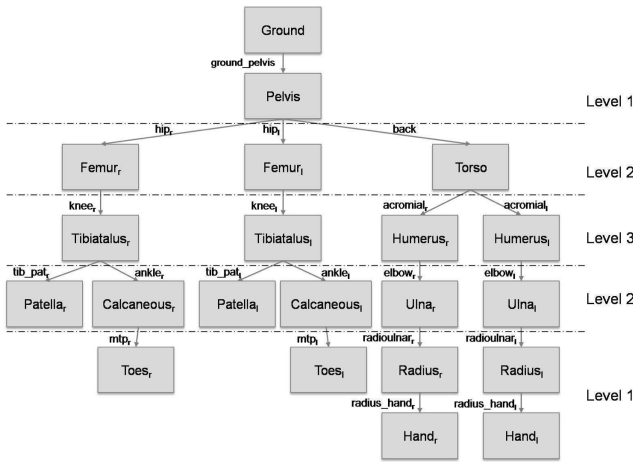


Fig. 2. The topology of the skeletal model following the natural tree-like branching structure. Each block represents a body segment that is connected to its parent body by the corresponding custom joint. The subscripts r and l denote the right and left body parts, respectively [5].

The feasible range of accelerations can be determined using (6) given the bounds on the muscle induced torque capacities by,

$$0 < \Gamma < L^T m_{\max} \quad (3)$$

As examples illustrating dynamic skills, we characterized the throwing motion of a professional football player and the full golf swing of an elite golfer. In our approach, the performance that suits both players can be defined as the ability to achieve maximal ball velocity given the physiological constraints of the system (i.e. limb length, joint range of motion, and muscle strength and contraction velocity). The physiological constraints that affect human motion include the joint constraints (the range of motion at a joint), the segment constraints (the lengths of each segment) and the muscle constraints including physiological cross-section of a muscle, maximum contraction velocity, moment arm and line of action. The football throwing and the golf swing motions were recorded using an 8-camera Vicon motion capture system (OMG plc, Oxford UK) at a capture rate of 120 Hz and the simulations were generated in OpenSim and SAI [2] frameworks for the analysis.

The results of the characterization based on the muscular effort minimization function by analyzing an American football throwing motion showed that human hand trajectory follows the direction associated with the minimum effort (Fig 3.) [6]. Additionally, we characterized hand accelerations at a series of configurations along the throwing motion. The results showed that hand movement follows a trajectory with the direction of largest available acceleration during the performance of learned skills (Fig 4.) [6].

The full swing of an elite golfer was created in OpenSim using the motion capture data (Fig. 5). Here a golf club (9 iron) was added to the simulation and its inertia was calculated using [9]. The inverse kinematics was performed on the full body musculoskeletal model explained in Section II to calculate the joint angles for the full swing. Figure 5 illustrates the backswing (leftmost), downswing



Fig. 3. Task-based analysis of muscular effort. The muscle effort variation for selected 5 configurations during a throwing motion represented by ellipsoid expansion model. The throwing hand trajectory follows the direction of the ellipsoid associated with the minimum effort [6].

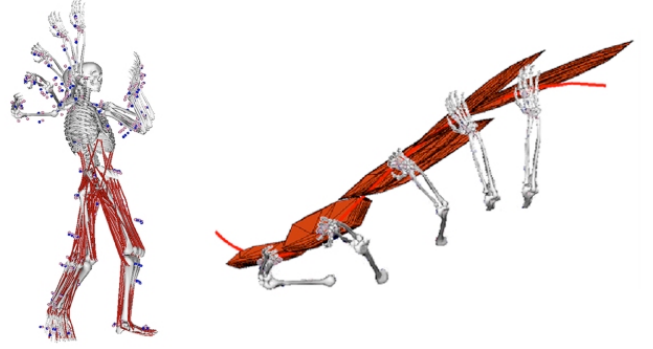


Fig. 4. The feasible set of accelerations for selected 5 configurations of a throwing motion. The throwing hand follows the direction defined by the maximum acceleration at each configuration [6].

(center) and the follow-through (rightmost) phases, respectively.

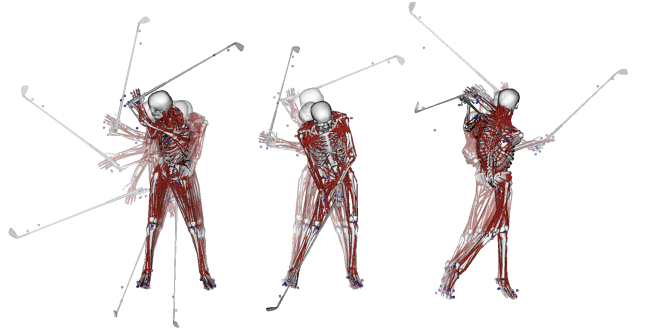


Fig. 5. Full swing simulation of a professional golfer using the musculoskeletal model explained in Section II.

V. CONCLUSION AND FUTURE WORK

We presented a robotics-based whole-body marker tracking control method for the task-level reconstruction of human motion and a novel motion characterization approach to extract task-driven human performance metrics in professional athletes.

The characteristics and criteria associated with a human skill may serve as a real-time visual feedback tool in motion restoring and athletic training. They may also be used to predict injury-causing motion patterns or to synthesize subject-specific optimal movement.

Our ongoing work on robotics-based analysis of human motion will include the motion characterization of the elite golfer's swing introduced in Section IV. This approach of learning skills from human will be applied to predict new motion patterns for achieving optimal performance and can be used to accelerate learning a new skill or reduce the risk of injury.

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