Human Motion Reconstruction and Multi-Modal Feedback for Pathology Evaluation, Therapy Delivery, and Athlete Training - II

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Purpose and Goals of Research

This research will extend our previous work to develop a human motion reconstruction and multi-modal feedback system to monitor, analyze, and provide immediate feedback to subjects regarding the motions, forces, and stresses of their limbs, muscles, and joints. This work will fundamentally advance technology for human simulation and have important applications in preventing musculoskeletal injury and disease as well as improving athletic performance. This proposal integrates four significant contributions to our previous work:

1. **Human motion atlas development**. Our previous work developed algorithms to compute complex human motion dynamics from tracked optical markers in real-time. We will apply these algorithms to analyze and document human motion trajectories for different tasks executed by subjects of different skill level. *Our goal is to build a generalized human motor-control atlas* that will describe optimal motion trajectories for any individual to improve performance or reduce risk of injury.
2. **Real-time joint stress analysis**. Our previous analysis tools allowed us to estimate the muscle forces responsible for producing complex human motion. We will extend this framework to incorporate surrogate contact algorithms to estimate bone-on-bone joint stresses. *The long-term goal of this work is to provide tissue-level stresses as feedback to subjects in real-time*.
3. **Novel algorithms for optimal and pathological motion pattern characterization**. Our next aim is to classify motion characteristics (from trajectories to muscle forces and joint stresses) as desirable or detrimental, and identify the best modes of feedback to correct pathologies. We plan to identify the motor pathologies, and the optimal modes of feedback, using computationally efficient *decision trees*. Decision trees will be built that can associate tracked motion with the closest optimal motion from the atlas and suggest multi-modal feedback to approach the optimal, all in real-time.
4. **Multi-modal feedback development.** Previously, we implemented vibration, vision, and skin stretch separately as one degree-of-freedom real-time feedback in order to improve human gait. Each of these individual modalities provided distinct advantages for the user. This work will be extended by combining novel and existing modalities into a powerful multi-degree-of-freedom feedback mechanism. The final aim of this project is to *develop and explore the limits of such a complex multi-model feedback system for motion training and rehabilitation.*

Expected Outcome and Impact

The computational developments proposed will extend our tools to estimate joint and tissue stresses and enable us to characterize optimal and pathological human motion and provide optimal feedback to an individual. The impact of this human motion atlas and feedback tool is profound. For example, our recent research illustrated the efficacy of real-time motion reconstruction and haptic feedback by reducing individual knee joint loads during walking up to 50% within one training session (Figure 1). This gait-retraining tool has implications for reducing the onset of knee joint osteoarthritis (OA), a degenerative joint disease whose progression is linked to knee loading during gait. Knee OA affects millions of people worldwide and costs billions of dollars in associated health care costs and reducing the progression of this disease will have huge societal impact.

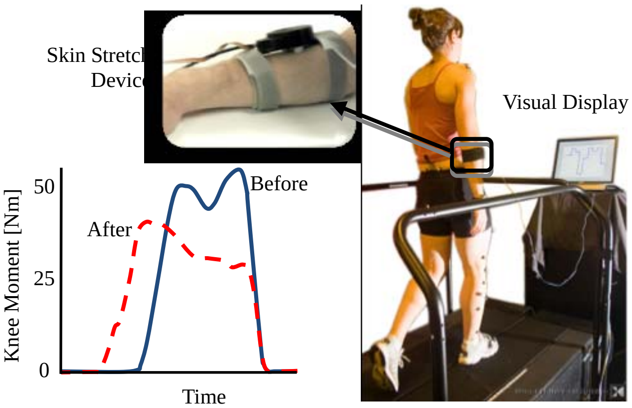

Figure 1. Knee adduction moment before and after real-time feedback

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Background and Previous Work

Over the past year, we have integrated fast algorithms for characterizing human movement with musculoskeletal simulations, and have built a tactile feedback device that alerts subjects to excessive joint loads by stretching their skin. The highlights of our research are:

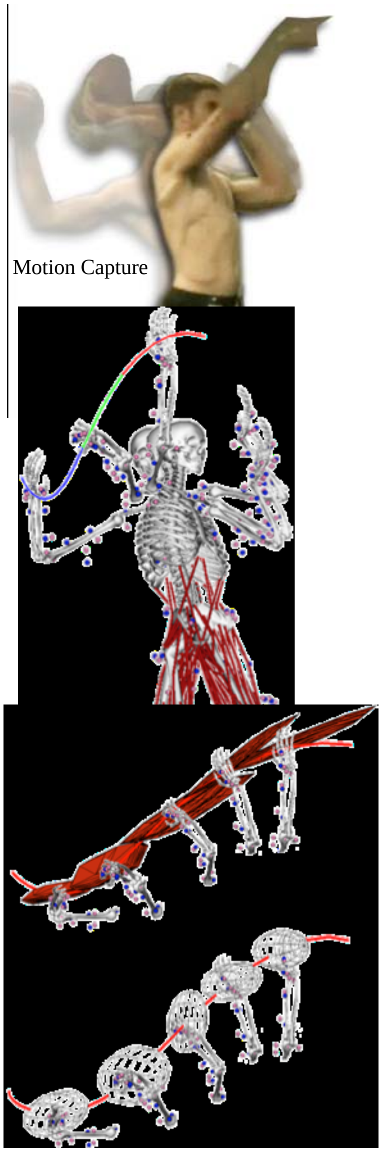

Figure 2. Dynamic human motion reconstruction and performance characterization of throwing.

Dynamic motion reconstruction: We developed and implemented a new algorithm to reconstruct human kinematics from motion capture data [4]. The algorithm leverages operational space [8] and whole-body control [7] methods to directly emulate Cartesian marker trajectories using human musculoskeletal models, and eliminates complicated inverse kinematic computations.

Performance characterization: To characterize and model human motion performance, we have recently developed a novel method based on acceleration and effort analysis of athletic motions. This method takes into account skeletal kinematics as well as muscle routing kinematics and physiologic force generating capacities. Our analysis of the characteristics of human motion supports the hypothesis that humans utilize their mechanical advantage to execute athletic skills while dealing with physiological constraints [2, 6].

Real-time motion capture and musculoskeletal modeling: Our dynamic multi-contact, multi-body simulation framework, SAI (Simulation & Active Interface) has been integrated with our real-time Vicon motion capture system. SAI provides a unified set of tools to simulate the dynamic behavior and control of virtual human subjects and provides a sophisticated computational framework for solving problems in biomechanics and sport medicine. Our current control and simulation framework incorporates the dynamic motion reconstruction and EMG-informed muscle force tracking algorithms with biologically accurate human musculoskeletal models in real time. The integration of Vicon with SAI enables us to transfer and process real-time marker and force data into the reconstruction and modeling framework.

EMG-informed muscle force tracking: To extract muscle activation patterns during human performance, we have developed and implemented a system that integrates Computed Muscle Control (CMC) [11] with electromyographic (EMG) data. *EMG-informed CMC* estimates muscle forces by adding the experimental EMG data to the original optimization criteria, providing physiologically-based muscle activation patterns [3].

Wearable tactile device and real-time feedback: To augment visual feedback of desired motion trajectories, we developed and tested a novel tactile device. The performance of a wearable skin stretch display has been evaluated in open and closed-loop tasks [1]. We have also integrated the device controller with our musculoskeletal modeling environment for real-time feedback during motion training.

Research Plan

Aim 1. Human motion atlas development

We will develop new metrics to accurately model and evaluate human motion performance patterns. The resulting models will provide us with extensive physiological information, which previously was only accessible through invasive clinical procedures. Using this information, we will analyze in detail the biomechanical variables of the real-time motions, and decide which variables play an important role in optimizing the performance. Examples of metrics include: (1) ‘Muscle-level’ fatigue and failure criteria models based on calcium release. (2) Joint postural gravity and acceleration-based effort expenditure criteria. (3) Muscle capacity models for goal-based motion tasks. More generally, we will strive to develop new criteria that correlate to the observed motion characteristics of humans, which will include physiological, kinematic, and dynamic performance parameters.

To realize the proposed analysis and guidance system, we will develop an advanced bio-computational platform. This platform will involve motion reconstruction and EMG muscle force tracking systems, musculoskeletal, kinematic, and dynamic models of the subjects, performance evaluators, and real-time feedback control interfaces. Some of these modules will be leveraged from our current platforms for control of humanoid robots including efficient kinematic and dynamic computational algorithms, balance and contact stability estimators, gait planners, whole-body task and postural controllers. A new module will be developed to implement the optimization policies from humans and another one will be developed to guide the real-time motion to optimal paths.

Our computational platform will first be used as an analysis tool providing combinations of parameters that we can correlate with human performance. This step will facilitate the development of new criteria for performance analysis. In a second phase, we will use our computational system to guide and improve human motion. These criteria will automatically suggest modified trajectories for optimal performance. Finally, the suggested trajectories will be presented to the subject using a combination of visual and/or haptic devices.

Aim 2. Real-time joint stress analysis

We will extend the human motion atlas created in the SAI environment to incorporate surrogate contact models for estimating internal ‘bone-on-bone’ contact forces, in real time. We will base these contact models on an elastic foundation method [5] and connect them to our dynamic motion reconstruction algorithm. First, the articulating geometry of the joint of interest will be determined by segmenting the subject’s joints. The subject’s dynamics and contact forces will be obtained from the SAI simulation and be used together with the human motion atlas to provide more efficient motor feedback. For this purpose, our computational framework will be extensively developed to include new modules for the contact models as well as the performance evaluators and real-time feedback control interfaces for the human motion atlas. The knee joint (tibiofemoral and patellofemoral articulations) will be modeled initially as validation data are available in the form of motion and *in vivo* tibial force data collected from an individual with an instrumented knee prosthesis [9]. Ultimately, the real-time investigation of joint stress will significantly improve our capability to predict and diagnose joint injuries and disease, such as patellofemoral pain and knee joint osteoarthritis.

Aim 3. Novel algorithms for optimal and pathological motion pattern characterization

We will develop new algorithms to classify motion characteristics as desirable or detrimental when compared to the optimal motions in the human motion atlas. Identifying optimal and pathological motions fast enough to give corrective haptic feedback requires the creation of new computationally efficient motion classification algorithms. We believe that decision trees [10] will meet the challenge by converting motion classification into a search problem over the set of motions in the atlas, which may be solved efficiently. Decision trees can efficiently compare units of motion (such as a gait cycle or a golf swing) with the optimal motions in real-time, and can identify detrimental variations. Optimized trees may achieve real-time operation even for complicated multi-joint motions by spending more time classifying motions with high expected improvement and vice versa.

To design and implement the new motion characterization algorithms, we will analyze motions in detail

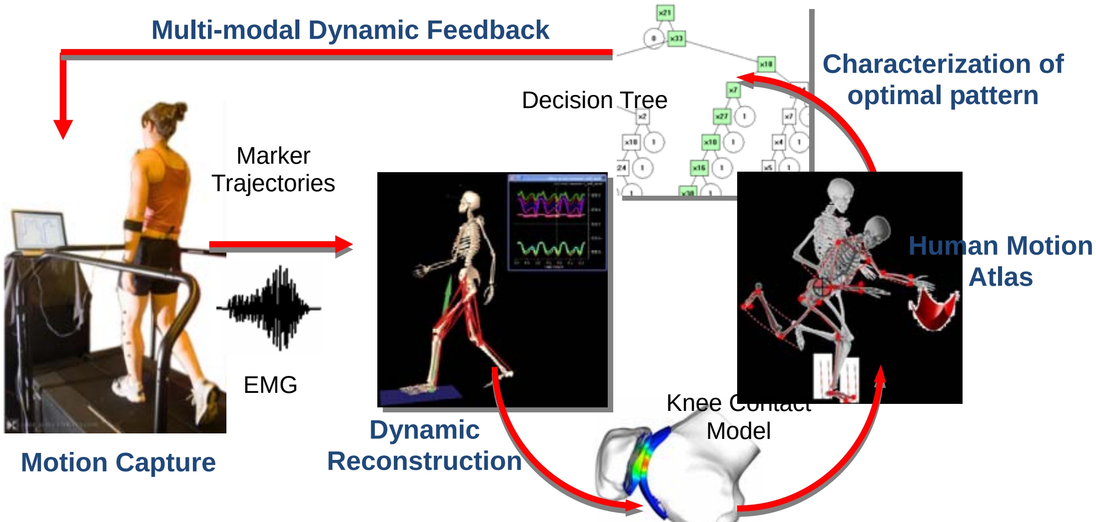

Figure 3. Dynamic human motion reconstruction and multi-modal feedback pipeline.

and identify the best possible modes of feedback for specific motions. In addition, we plan to experiment with multiple modes of feedback on live subjects to identify the best possible improvements in motor pathologies. This research will increase our understanding of human motor control from a clinical perspective and has the potential to have a strong impact on clinical practice.

Aim 4. Multi-model feedback development

We will develop a multi-degree-of-freedom system for real-time visualization and feedback. This system will utilize multiple devices with different types of display for coordinated motions. From previous testing we have observed that vision feedback provides a high degree of precision. Vibration provides simple and intuitive feedback, particularly when vision is otherwise occupied, and skin stretch allows the user to sense velocity and position simultaneously. Vibration conveys cartesian space directional cues well, while skin stretch may be more effective at joint space feedback. By integrating these devices, we can combine their advantages to provide rich and intuitive feedback for human motion optimization.

The development of such a system raises several questions such as: How many of each type of device should be used? Where on the body should the haptic feedback mechanisms be placed? How well can subjects interpret higher orders of simultaneous multi-modal feedback? We will conduct user studies and collect qualitative and quantitative data to answer these questions. As the limits and usability are understood, the multi-modal feedback system will be integrated with characterized human motion and soft-tissue algorithms for human motion training and rehabilitation.

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