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

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## Purpose and Goals of Research

The proposed research will make it possible to monitor, analyze and provide immediate physical feedback to subjects regarding the motions, forces and muscle activity of their limbs. The work will fundamentally advance technology for human simulation and have important applications in rehabilitation (e.g. relearning how to walk after a stroke) and athletics (e.g., perfecting a complex motion sequence). The research draws upon and integrates new results in three areas:

1. **fast algorithms** for computing and matching the dynamics of a complex human movements to the measured velocities of optical markers;
2. **musculoskeletal simulations** that predict the muscle forces and velocities associated with human movements;
3. **wearable tactile devices** that utilize a combination of skin stretch and vibration to provide users with an enhanced perception of joint movement and/or muscle force.

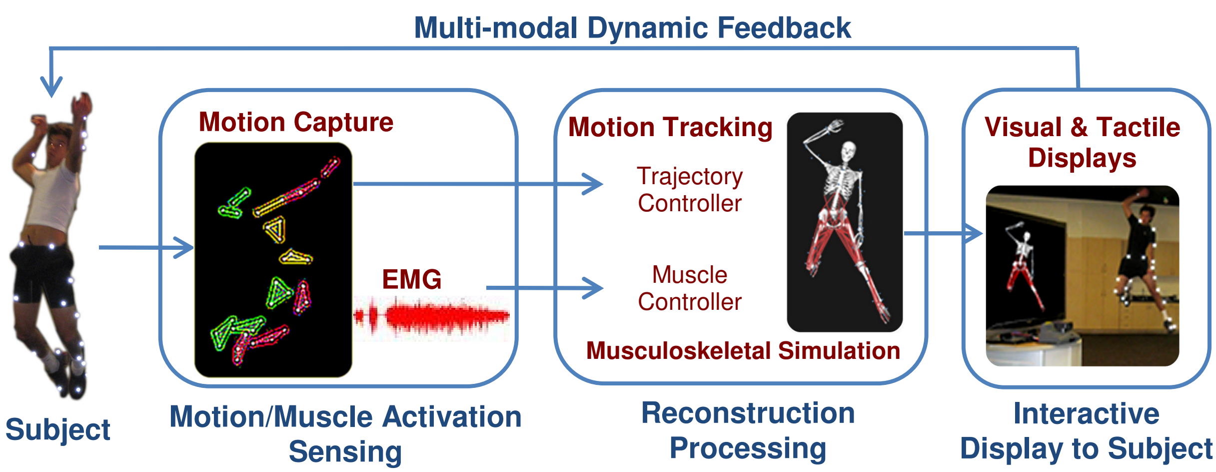


**Figure 1 -** Interactive Multi-Modal Feedback Mechanism

## Expected Outcome and Impact

This proposal brings together ground-breaking work in computer science, bioengineering and multi-modal human-computer interaction to produce a unique motion training capability. This work promises an unprecedented ability to provide subjects with real-time visual and physical feedback to correct or optimize their motions *while* they are executing them. In contrast, the current state of the art involves lengthy data acquisition, followed by post-hoc analysis, expert interpretation and recommendations that are potentially days or weeks following the initial assessment.

There are numerous benefits in providing motion training to alter the kinematics and loads on the musculoskeletal system. Gait retraining following knee ligament reconstruction, for example, may reduce the risk of early onset of osteoarthritis, saving millions of dollars in associated health care costs. Gait retraining with tactile feedback in stroke patients could dramatically improve ambulatory function and quality of life for these individuals. In sports, coaches and athletes continually strive to achieve the "perfect" or "ideal" motion and do so primarily through trial and error. This new motion training modality is capable of producing an optimal solution for any athlete, revolutionizing the world of athletic training. This proposal will drive advances in computer science directed toward these important societal needs.

## Background and Preliminary Work

**Dynamic reconstruction:** The sequence in Fig. 1 begins with dynamic reconstruction of human motion. Building upon algorithms and models developed in the context of humanoid robotics (Khatib et al., 2004) we have developed and implemented a novel muscle effort criterion for predicting physiologically accurate upper limb motion (Khatib et al., 2004, De Sapio et al., 2006). These developments were implemented in SAI (Khatib et al., 2002), a simulation and control environment developed to perform interactive task-level synthesis of complex robotic and biomechanical systems.

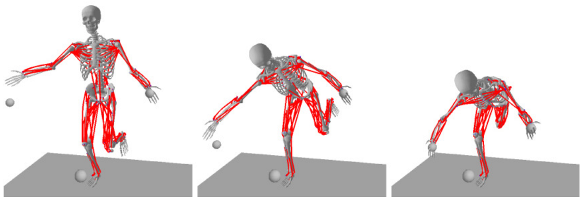

**Figure 2 -** Whole-body system can be simulated in SAI using a musculoskeletal model and controlled in real-time to synthesize and investigate human movement using a task-level framework.

More recently, we proposed and implemented a new algorithm to reconstruct human motion from motion capture data through direct control of captured marker trajectories. This algorithm uses the prioritized whole-body control framework (Khatib et al., 2008) developed for constraint handling. The approach directly projects marker points onto a simulated human model and tracks the trajectory in marker space. This algorithm was validated on a sequence of tai chi master motions and the results demonstrated its effectiveness in ensuring smooth tracking of marker trajectories and for the extraction of joint angles without costly inverse kinematics computations (Demircan et al., 2008). The study has also shown the algorithm to easily accommodate anthropometric scaling of the musculoskeletal model to human subjects.

**Musculoskeletal modeling and analysis:** The next stage in Fig. 1 is dynamic simulation of muscle activity. Simulations of movement allow one to study neuromuscular coordination, analyze athletic performance, and estimate internal loading of the musculoskeletal system. Simulations can also be used to identify the sources of pathological movement and establish a scientific basis for treatment planning. We have developed an open-source software system, OpenSim (Delp et al., 2007) that lets users develop models of musculoskeletal structures and create dynamic simulations of a wide variety of movements. We are using this system to simulate the dynamics of individuals with pathological movement and to explore the biomechanical effects of treatments.

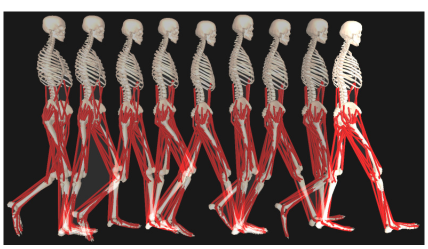

**Figure 3 -** Three-dimensional dynamic simulation of normal walking showing the model that will be used in these studies. We have used this model to create over 50 muscle-actuated simulations of normal gait and several simulations of crouch gait; this suggests that the model's degrees of freedom are sufficient to reproduce the salient features of normal walking and running.

**Tactile display:** The third stage in Fig. 1 involves interactive display of results to the subject. Wearable haptic feedback has been proposed as a way to augment or even replace visual or audio feedback for active people (Lieberman and Breazeal, 2007). Vibration is the most common feedback mechanism, but is imprecise at providing a sense of the magnitudes or velocities of motions. In most implementations, vibration feedback provides an "event cue," i.e., an indication that some, often exogenous, event has occurred.

For applications involving motion training and rehabilitation, skin stretch is a useful complement to the cues provided by vibration. Skin stretch excites some slow-acting mechanoreceptors and therefore does not need to be rapidly varying to elicit a proportional response. It is also a component of the human proprioceptive apparatus, particularly for the distal joints but also at the elbow and knee (Edin, 2001, Collins et al., 2005). These observations suggest that skin stretch display could be particularly useful for wearable devices in motion training for sports, physical rehabilitation or therapy, and in neurological conditions (e.g. stroke, multiple sclerosis) where afferent function is distorted or diminished.

In recent experiments (Bark et al., 2008), rotational skin stretch, applied to the hairy skin near the elbow, was more accurate than vibration in providing subjects with an estimate of the range and velocity of motion of a virtual arm. The tests were conducted with the subject's arm immobilized and with a "benchtop" apparatus for imparting controlled strains to the skin. However, the inherently low power requirements of skin stretch lend themselves to the design of compact wearable displays.

**Figure 4 –** Concept of portable skin stretch devices and photograph of "benchtop" prototype using piezoelectric rotary actuator to provide the subject with tactile feedback.

In addition to providing subjects with information about the motion of their limbs (which can also be conveyed visually) we expect that conveying real-time information about muscle force will be more intuitive using tactile displays. The ability to convey multimodal information is also important. For example, for neurological rehabilitation after surgery or stroke, we expect that providing proportional proprioceptive feedback will be most useful as subjects relearn movements. In athletic applications, where movements are often fast and highly stereotyped, we expect that providing discrete event cues may be more useful (e.g. alerting the subject that a particular muscle group has been activated too early or late in a golf swing or if the force in a muscle becomes high such that injury is likely).

## Research Plan

### Aim 1 - Measure motions and estimate limb and muscle dynamics

Interactive motion training requires high fidelity models of the musculoskeletal system. These models must predict the muscle forces associated with the observed motions of the human subject. The direct marker control algorithm illustrated in Fig. 5, will be extended to compute muscle excitations, activations, and resulting forces required to move the subject in accordance with marker trajectories. The result is a full, *dynamic biomechanical profile* that can be presented via visual and tactile feedback to facilitate motion training.

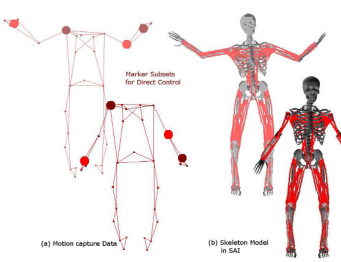


**Figure 5 -** The scaled human model of the tai chi master is simulated in the SAI environment. Markers of the right shoulder and the left wrist are selected to form the first marker set to be controlled (dark spheres). The second subset is formed by the left elbow and the right wrist markers (light spheres).

For this work, computational neuromuscular models will be developed using state of the art Hill-type models of muscle. These will be implemented as 1-dimensional muscle action models for real-time interactivity, and as 3-dimensional finite element models for higher fidelity off-line analysis. With regard to the control of the muscles spanning the skeletal system, it is assumed that the CNS issues motor commands to achieve a given task in a way that minimizes some neuromuscular cost/effort (subject to task requirements). While the precise nature of what is being minimized is difficult to directly infer, computational muscle models can be used to evaluate particular hypothetical effort criteria. Predicted excitation patterns associated with a hypothetical effort criterion can be validated against EMG measurements of selected muscles.

A library of muscle effort criteria will be discovered, validated, and mapped to our digital human atlas. Strength-based, fatigue-based, and failure-based criteria will be implemented in the atlas to characterize the broad domain of human movement. A particular physical activity may transition between multiple criteria. For example, initially a strength-based criterion may be dominant. In such a criterion the strength capacity of the muscles is considered and assumed to be time invariant. Subsequently, fatigue may set in and a time variant fatigue-based criterion will dominate. For extreme movements a failure-based criterion will dominate. Such a criterion considers failure mechanisms correlated to joint reaction forces which influence ligament strain. A task-level muscle controller will be developed and it will implement our library of muscle effort criteria. During simulation the marker trajectories will be tracked in real-time by controlling the muscle excitations in accordance with the relevant effort criteria. Based on the musculoskeletal model, muscle activations, muscle forces, and joint torques will be computed and displayed, along with any additional measurements (e.g., EMG or force plate data).

### Aim 2 - Develop algorithms for characterizing and comparing human performance

For the proposed work, we will create a 3D dynamic *human atlas* in SAI which will be used for the characterization of any arbitrary human movement. This atlas will provide a real-time display of the dynamic characteristics of human movements over the workspace. The characteristics we intend to dynamically display include mass/inertia properties, acceleration, joint torque, muscle force and activation patterns. We will use these characteristics to extract criteria that the subject attempts to optimize during his/her movements. For this purpose, our work will be based on the human motion reconstruction algorithm that we introduced recently and energy minimization criteria that seek the optimal movement for a given task. Additionally, our reconstruction algorithm will include an adaptation mechanism to adjust to unknown subject anthropometry through elastic elongation limb lengths. A unique feature of the proposed work is that the human atlas will be used directly for patient therapy and training of athletes, through 3D real-time visual and tactile display.

### Aim 3 - Test subjects' perception and performance with new tactile and visual displays

For the proposed work a compact, *wearable skin stretch display* will be developed by October 2008, following the principles in (Bark et al., 2008) and actuated using a miniature piezoelectric motor for its combination of low weight and exceptionally smooth rotation at low speeds. (For vibration, actuators are readily available.) Prior to completion of the new skin stretch display, we will focus on event cues, to determine, for example, which combination of visual display and vibration patterns is most effective at helping subjects to avoid excessive strain. Upon completion of the skin stretch display, we will test it singly and in combination with vibration and visual display, to determine the latency, resolution and dynamic range with which subjects perceive variables related to joint and limb motion.

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