It's One Small Step For Man, One Giant Leap For Computer Simulation

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The ability for computers to simulate complex mathematical models has dramatically increased in the last decade. Although the processing power of a single CPU continues to steadily increase each year, it is the reduced CPU costs that allow the creation of large networked computing clusters to perform parallel computations that is exciting those involved in computer simulation. One promising utility that takes advantage of parallel computations is the study of human movement.

The human musculoskeletal system is a mechanical linkage consisting of a set of body segments, all connected by articulating joints, and actuated by musculotendon units. Each musculotendon unit is itself a complex physiological system consisting of pennated muscle fibers with physiological properties that govern how pulses of electricity sent from the central nervous system (CNS) ultimately lead to force development. The muscle fibers are connected to elastic tendinous tissue, which transmits this force to the bone, accelerating the joints into motion. In this regard, the dynamics of the human body are governed by Newton's second law, F=ma: muscle fibers are excited by signals from the CNS and develop force, which is transmitted to bone, generating rotational accelerations in the joints. Given initial conditions to this system, numerical integration can be used to dynamically simulate human motion forward in time.

What makes simulating human movement challenging is closing the loop between the simulated motion and the CNS neural signal. Humans have an acute proprioceptive sense of being, which is difficult to quantify and extremely challenging to correlate to CNS activity. Furthermore, our senses can also dictate how we activate our muscles, for example, falling through midair and landing on an inclined surface, one would recruit their muscles differently being able to see the landing surface versus being blinded. An important active area of study is that of quantifying different forms of perceptive feedback to the magnitude of CNS signal developed by each specific muscle group in the lower limbs. Given a set of muscle feedback laws, (Fig. 1), the musculoskeletal system can be numerically integrated in closed loop form to capture the model's response to the simulated surrounding environment.

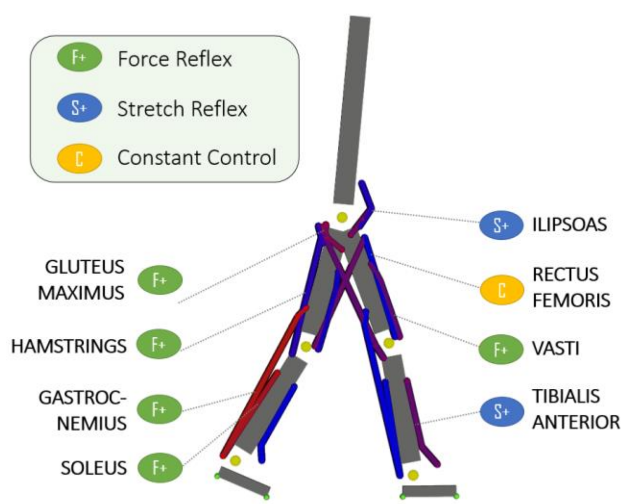

Figure 1: Muscles actuate the model into motion and are controlled with physiologically motivated reflex controllers.

This is where parallel processing yields its immense power. The muscle control laws are parameterized by many variables (i.e., gains, thresholds), which dictate the stability of the simulation as well as other aesthetic walking properties such as style, speed, stride length and stride frequency. It is possible to optimize these parameters to generate predictive simulations of a specific walking scenario by minimizing an objective function. For example, normal walking (Fig. 1) involves minimizing metabolic energy whilst keeping the joints within physiological ranges of motion. The optimization process requires thousands of simulations to find the most optimal solution, and these individual simulations can be executed independently and simultaneously on a parallelized computer cluster (Fig. 2), achieving computational speedups orders of magnitude greater than execution on a single CPU.

What does the future hold? Predicting patterns of human motion has applications in both biomechanics and robotics. For example, orthopedists could plan musculoskeletal corrective surgeries for those with movement disorders such as spastic cerebral palsy. This may be achieved by quantitatively exploring and refining surgical options, such as tendon lengthening, based on the simulation's predicted capacity to restore normal walking dynamics (Fig. 3), all before the patient enters the operating theatre. Predictive simulations can also assist with the design process of robotic assistive devices, such as exoskeletons, by providing the capability to test design prototypes on simulated humans rather than enduring the costly and timely process of manufacturing each device iteration and conduct explicit human testing. Such computational tools in conjunction with the surge in parallel processing represent a giant leap in technology with the potential to improve mobility and restore a high quality of life in those with walking impairments.

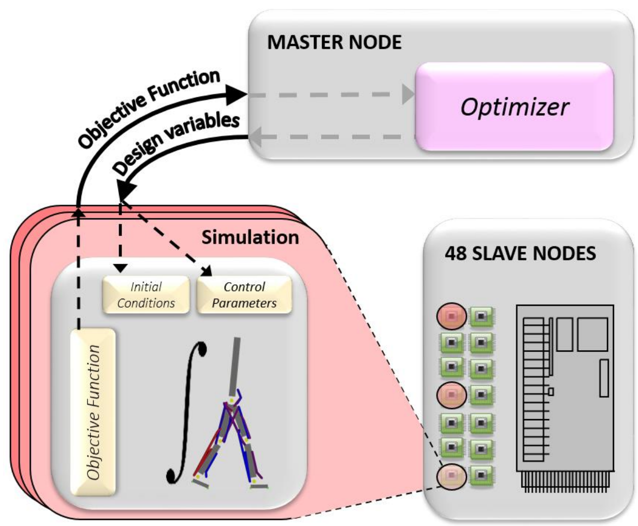

Figure 2: Parallelizing musculoskeletal simulations on a computer cluster to predict optimal human motion.

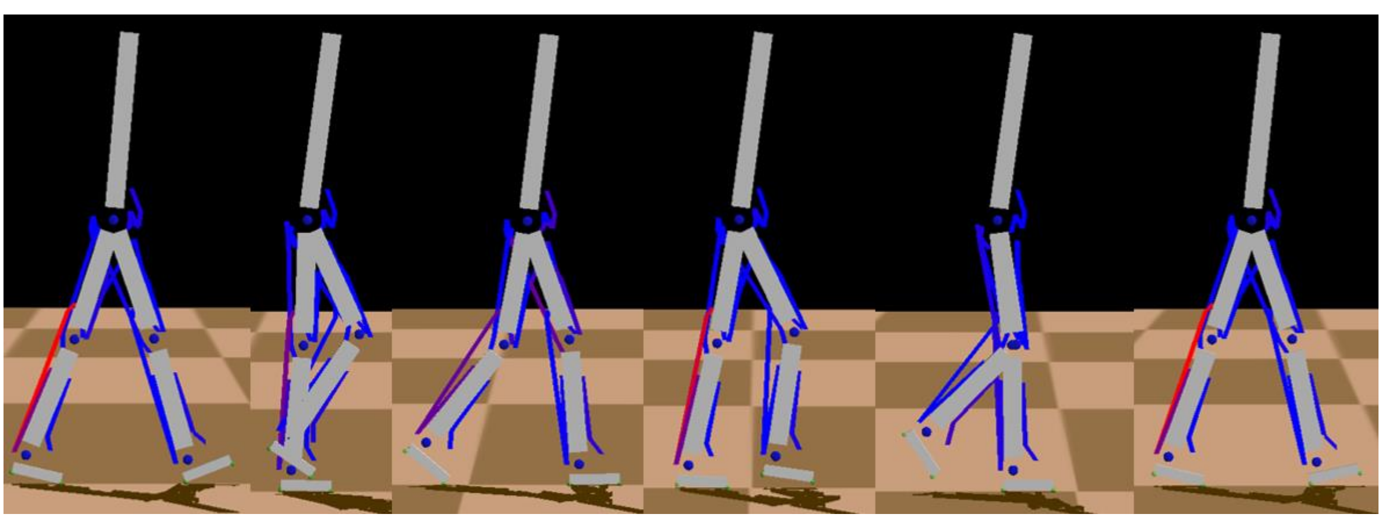

Figure 3: Simulated predictions of normal human walking, derived from the optimization without experimental data.