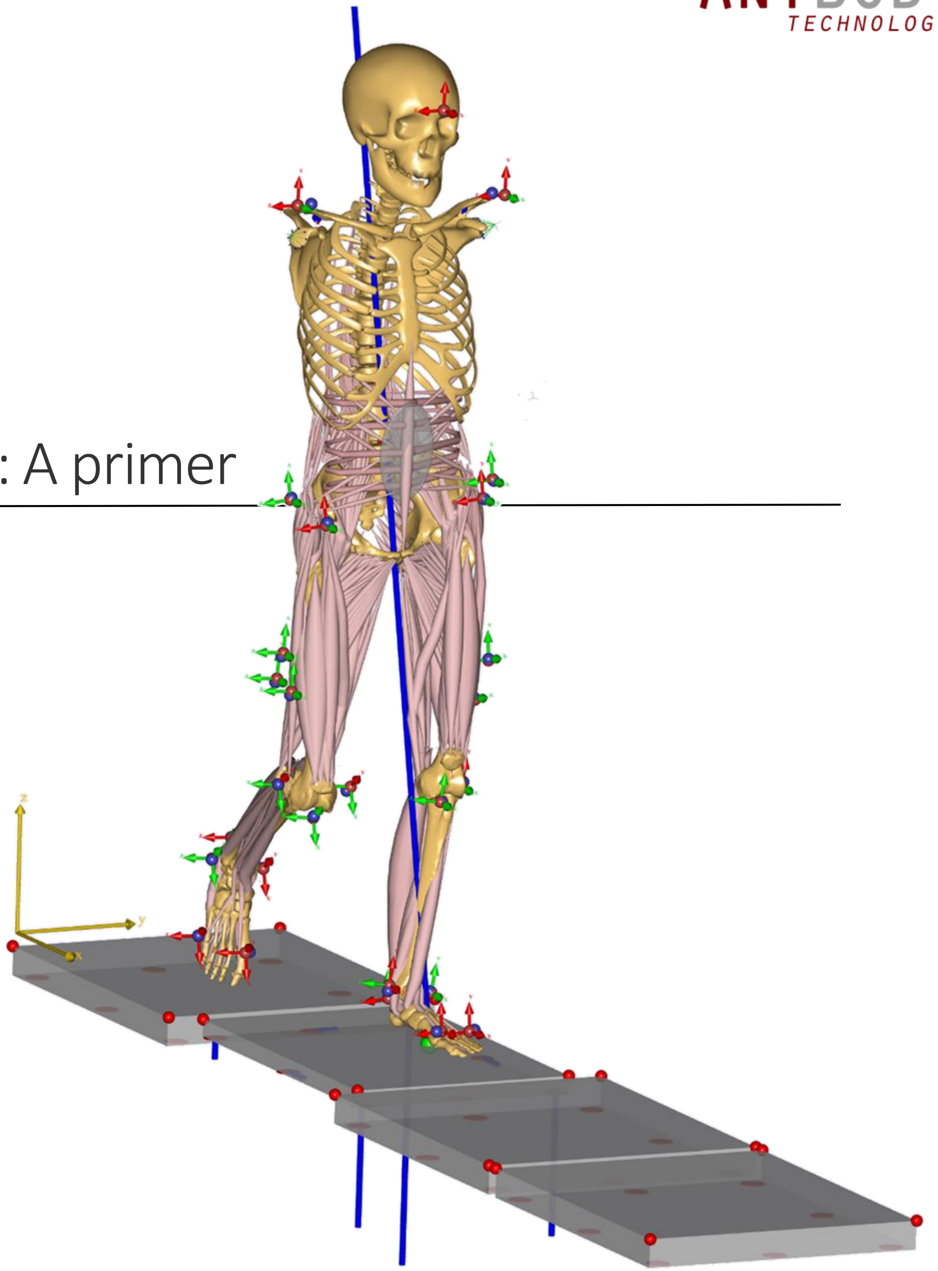
The webcast will begin shortly…

Musculoskeletal modeling for the evolutionary biologist: A primer

October 12th, 2021



Outline

- General introduction to the AnyBody Modeling System
- Presentation by Dr. Adam D. Sylvester
  - Musculoskeletal modeling for the evolutionary biologist: A primer
- Upcoming events
- Question and answer session

Presenter:
Dr. Adam D. Sylvester
Associate Professor

Center for Functional Anatomy and Evolution
The Johns Hopkins University School of Medicine

CENTER FOR FUNCTIONAL ANATOMY & EVOLUTION | JOHNS HOPKINS SCHOOL of MEDICINE

Host(s):
Bjørn Keller Engelund
R&D Engineer

Kristoffer Iversen
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Control Panel

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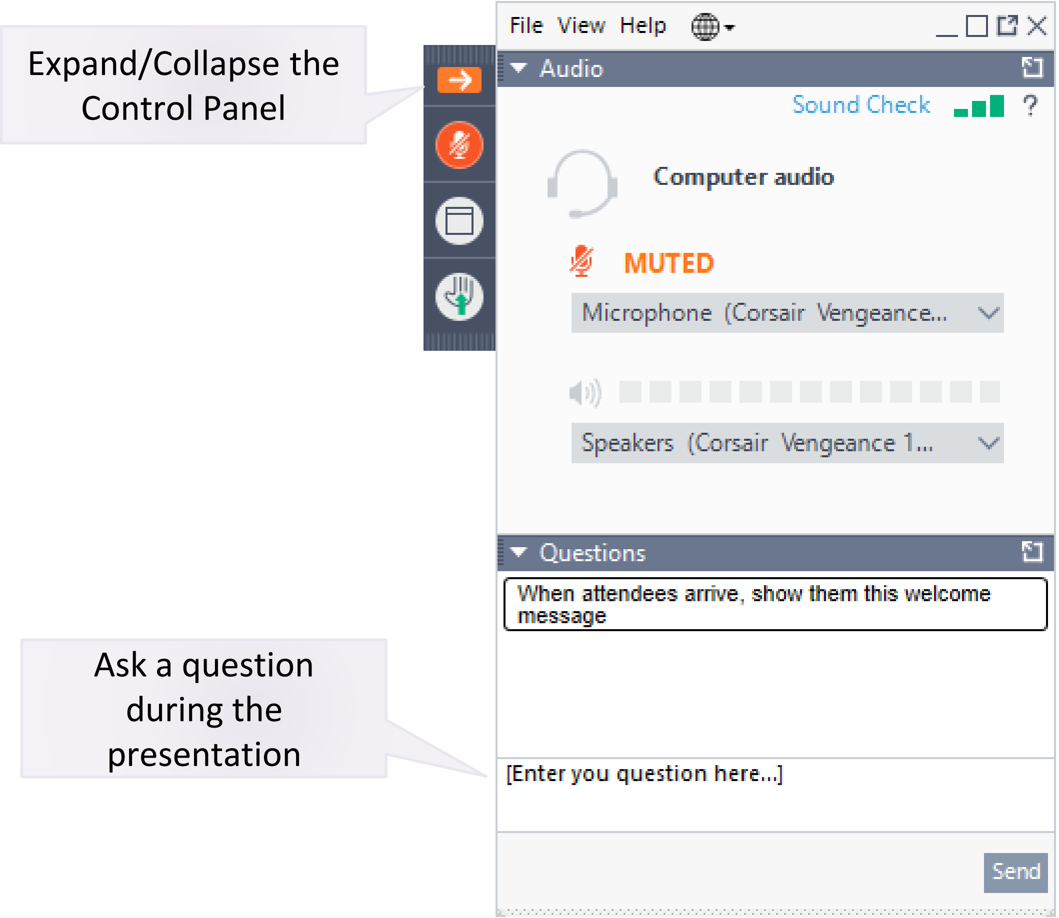
Submit questions and comments via the Questions panel.

> *Questions will be addressed at the end of the presentation. If your question is not addressed, we will do so by email.*



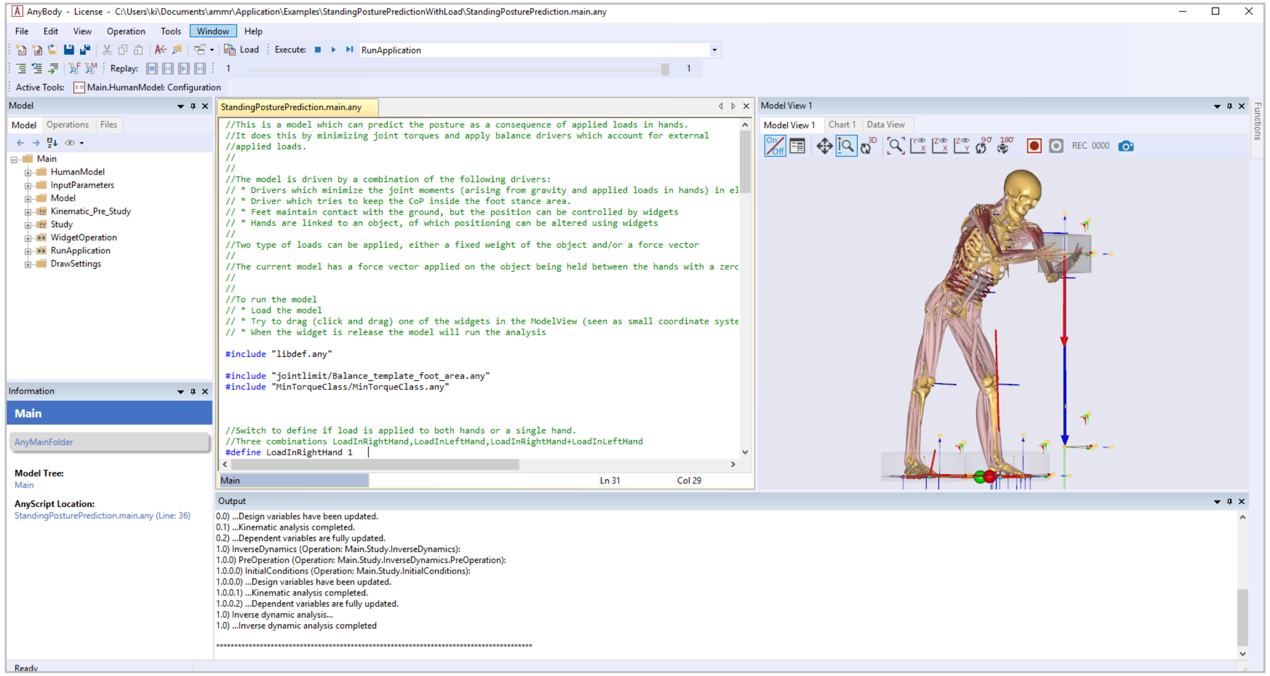
ANYBODY TECHNOLOGY

Musculoskeletal Simulation

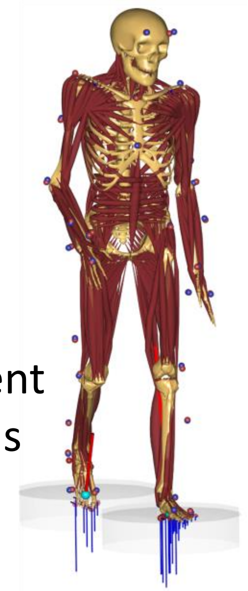
Motion Data
Kinematics and Forces

ANYBODY
Modeling System

Body Loads
- Joint moments
- Muscle forces
- Joint reaction forces

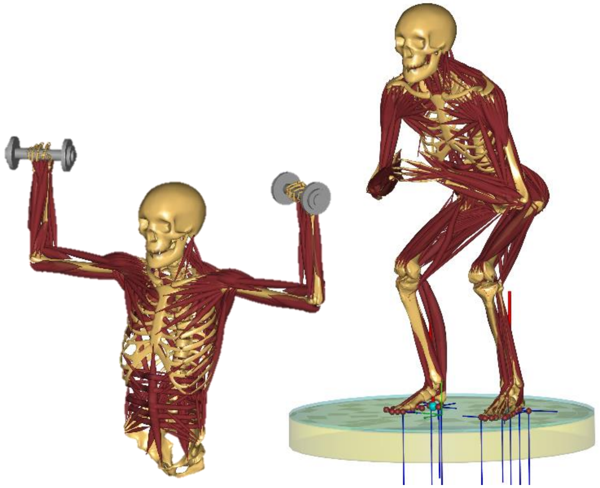


ANYBODY TECHNOLOGY



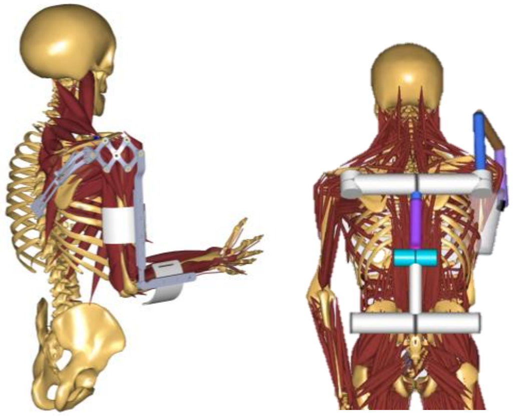
Movement Analysis

Product optimization design

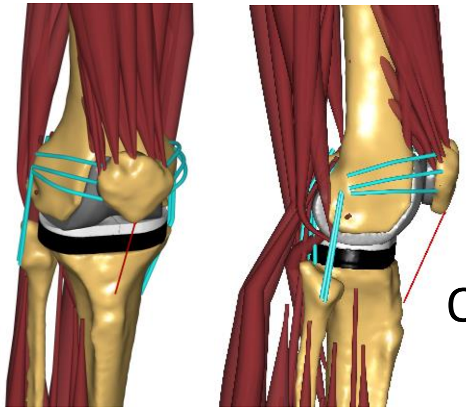


Sports

ANYBODY Modeling System



Assistive Devices



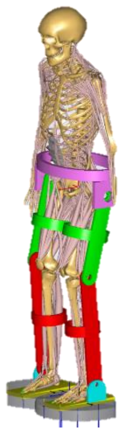
Orthopedics and rehab

AnyBody Modelling System

Motion and Forces

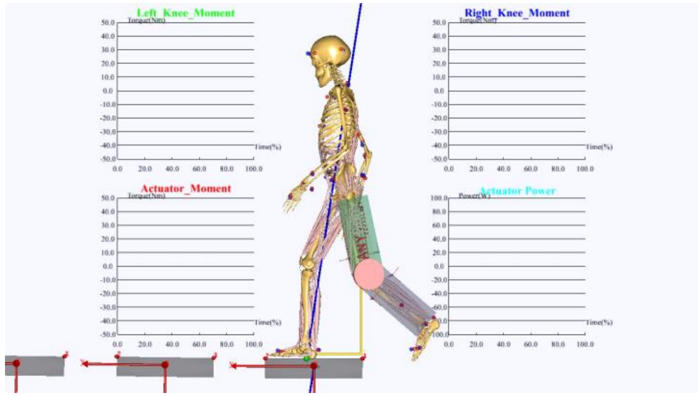
Body model

Environment model



Inverse dynamics
Muscle recruitment

Simulation



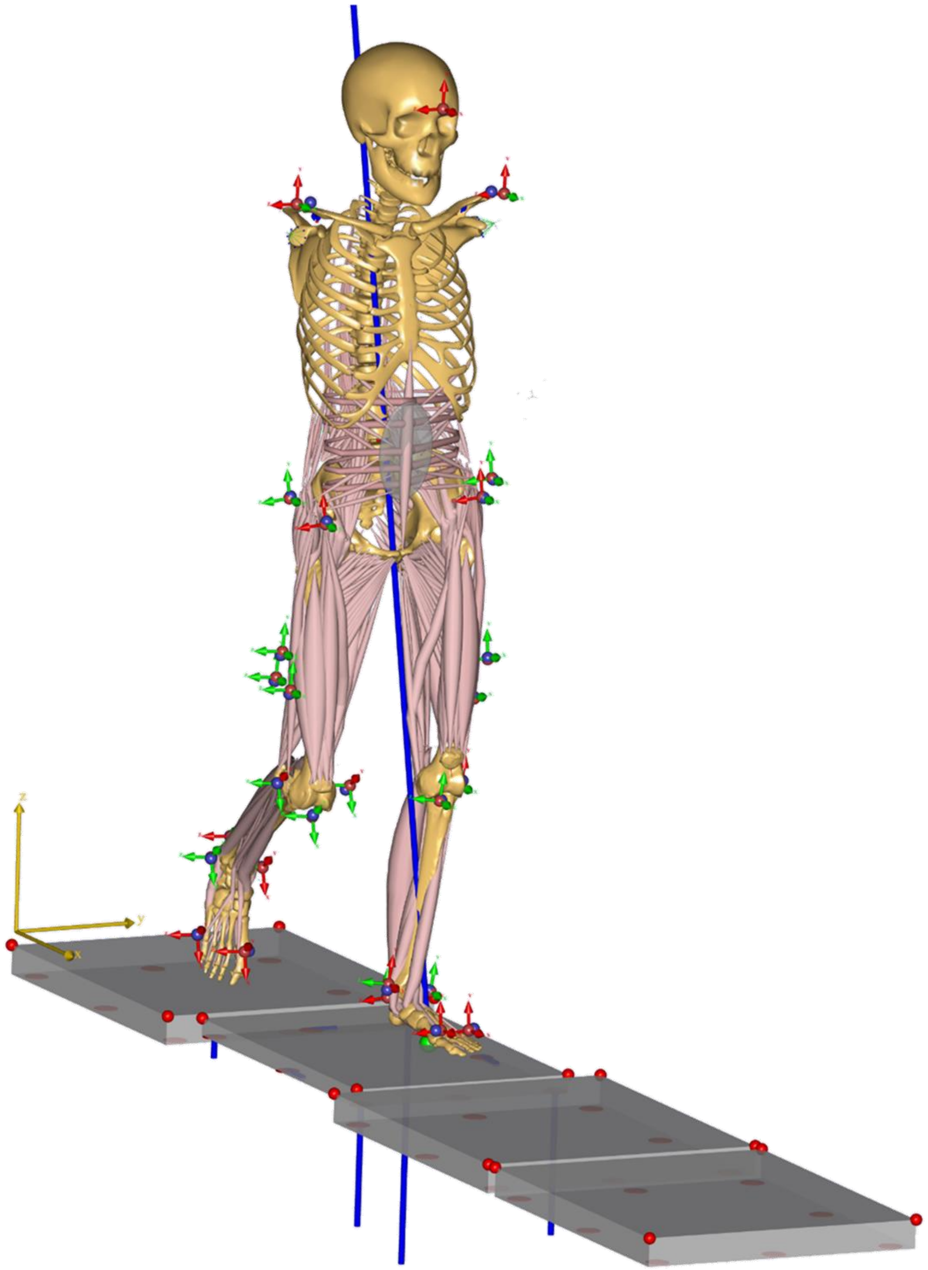
Internal body loads
- Muscle forces
- Joint moments

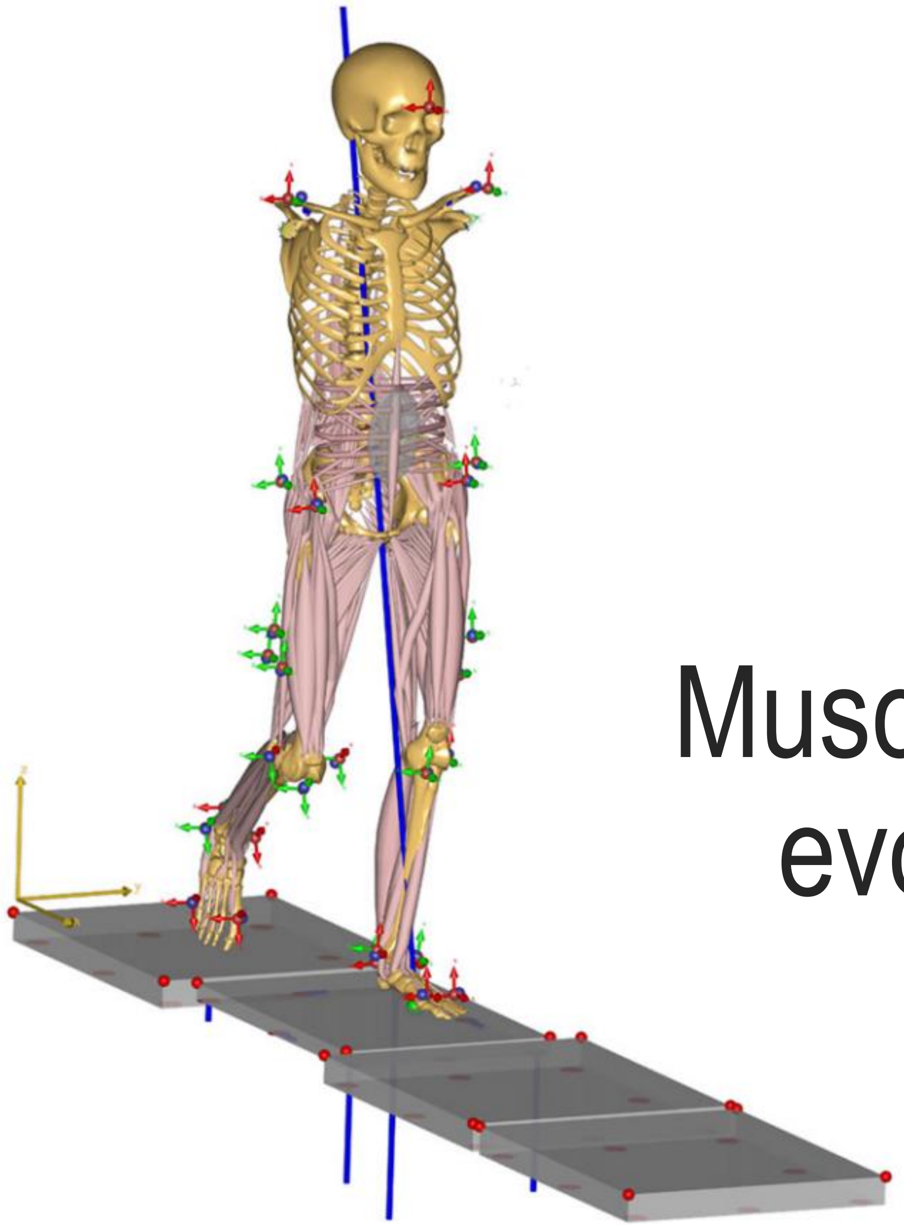
Design Optimization

Post Processing (e.g. Finite element tools)

Musculoskeletal modeling for the evolutionary biologist: A primer

Presented by Dr. Adam D. Sylvester





Musculoskeletal modeling for the evolutionary biologist: A primer

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Review

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One contribution of 12 to a theme issue 'Biological anthroengineering'.

Subject Areas:
biomedical engineering, biomechanics, computational biology

Keywords:
joint forces, muscle forces, biological anthropology, engineering, gait, evolution

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THE ROYAL SOCIETY
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A review of musculoskeletal modelling of human locomotion

Adam D. Sylvester[1], Steven G. Lautzenheiser[2,3] and Patricia Ann Kramer[2]

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Locomotion through the environment is important because movement provides access to key resources, including food, shelter and mates. Central to many locomotion-focused questions is the need to understand internal forces, particularly muscle forces and joint reactions. Musculoskeletal modelling, which typically harnesses the power of inverse dynamics, unites experimental data that are collected on living subjects with virtual models of their morphology. The inputs required for producing good musculoskeletal models include body geometry, muscle parameters, motion variables and ground reaction forces. This methodological approach is critically informed by both biological anthropology, with its focus on variation in human form and function, and mechanical engineering, with a focus on the application of Newtonian mechanics to current problems. Here, we demonstrate the application of a musculoskeletal modelling approach to human walking using the data of a single male subject. Furthermore, we discuss the decisions required to build the model, including how to customize the musculoskeletal model, and suggest cautions that both biological anthropologists and engineers who are interested in this topic should consider.

1. Introduction

A principal research focus within biological anthropology is interpreting skeletal variation within the context of behavioural diversity, including variation in diet, disease processes and activity patterns among living and extinct primates, including humans and hominins [1–4]. Locomotor behaviour and musculoskeletal morphology have been a central focus of this area of inquiry because locomotion provides primates with access to key evolutionary resources including food, shelter and mates. Furthermore, bipedalism is considered a defining character of the hominin lineage, cementing its importance within the field [5–7]. The challenge of elucidating form–behaviour relationships are the complexities of the intervening and underlying functions (e.g. joint range of motion) and biomechanics (e.g. joint reaction forces).

Early anthropological research connecting form and function was both typological and qualitative in nature; however, anthropologists have increasingly adopted mechanical engineering approaches to answer questions about primate locomotion generally, and hominin locomotion in particular (see [4] for a historical review). Within anthropology, two major subfields of mechanics have been applied to locomotor systems: Newtonian mechanics and solid continuum mechanics. Newtonian mechanics is concerned with the description of the motion of solid bodies under the influence of a system of forces, while solid continuum mechanics quantifies the behaviour (e.g. deformation) of solid materials when subjected to forces [8,9]. Lovejoy and colleagues [10–13] were early adopters within anthropology of both Newtonian mechanics and solid continuum mechanics [4]. Newtonian mechanics is routinely used by anthropologists to investigate a variety of questions (e.g. [14–19]). Beam theory, an application of solid continuum mechanics, has been used to estimate the structural capacity of long bones and is regularly exploited by anthropologists (see

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RESEARCH ARTICLE

Muscle forces and the demands of human walking

Adam D. Sylvester[1,*], Steven G. Lautzenheiser[2,3] and Patricia Ann Kramer[2]

ABSTRACT

Reconstructing the locomotor behavior of extinct animals depends on elucidating the principles that link behavior, function, and morphology, which can only be done using extant animals. Within the human lineage, the evolution of bipedalism represents a critical transition, and evaluating fossil hominins depends on understanding the relationship between lower limb forces and skeletal morphology in living humans. As a step toward that goal, here we use a musculoskeletal model to estimate forces in the lower limb muscles of ten individuals during walking. The purpose is to quantify the consistency, timing, and magnitude of these muscle forces during the stance phase of walking. We find that muscles which act to support or propel the body during walking demonstrate the greatest force magnitudes as well as the highest consistency in the shape of force curves among individuals. Muscles that generate moments in the same direction as, or orthogonal to, the ground reaction force show lower forces of greater variability. These data can be used to define the envelope of load cases that need to be examined in order to understand human lower limb skeletal load bearing.

KEY WORDS: Musculoskeletal model, Biomechanics, Lower limb

INTRODUCTION

Reconstructing the locomotor behavior of extinct taxa is the attempt to reverse engineer an organism's behavior from a selection of its morphology (Sellers et al., 2005; Nyakatura et al., 2019). Paleontologists are typically limited to tissues that fossilize well (i.e. skeletal elements, teeth), and the endeavor is made more challenging by the fact that skeletons and skeletal elements are rarely complete (Sellers et al., 2005; Nyakatura et al., 2019). The mandate of this line of inquiry is to determine the ways in which the skeletal system reflects the demands of locomotion.

The mammalian locomotor skeleton can be viewed as a series of rigid levers that are connected at articulations and actuated by muscles. Skeletal elements allow muscles forces to be transmitted and applied to the environment/substrate, which produces animal motion. Skeletal elements must be able to withstand the structural demands of forces applied by muscles, adjacent skeletal elements, and the substrate (Martin et al., 2015). Thus at a basic level, the skeletal system reflects the forces associated with locomotion. Such form-function relationships are informed by studying extant organisms, and then extinct taxa can be understood by projecting principles into the past. That is, reconstructing past behaviors requires evaluating the skeletal performance of extinct animals, which in turn necessitates discerning the principles that link behavior (e.g. walking), function (e.g. forces and load bearing), and morphology (e.g. femoral shape) using extant animals.

As bipedalism is one of the foundational transitions in human evolution, understanding the adaptive origin of hominin bipedalism remains a critical task and one that ultimately depends on elucidating the details of earlier forms. Based on fossilized skeletal material, various researchers have argued that most, if not all, extinct hominins practiced forms of bipedalism that were kinematically, kinetically, and/or metabolically distinct from modern human bipedalism (e.g. Stern and Susman, 1983; Kramer, 1999; Wood and Collard, 1999; Simpson et al., 2008; Lovejoy et al., 2009; Been et al., 2012; Ruff and Higgins, 2013; DeSilva et al., 2013). Much of this research has focused on the femur and pelvis because of the critical role these structures play in weight-bearing and hominin locomotion, and these bones contain features that are universally agreed to indicate bipedalism, while also potentially revealing the uniqueness of earlier forms (e.g. femoral bicondylar angle, Johanson and Taieb, 1976; femoral neck cortical distribution, Ruff and Higgins, 2013; short and wide pelvis, Lovejoy et al., 2009).

Leveraging a model adopted from human orthopaedic biomechanics, Lovejoy and colleagues (Heiple and Lovejoy, 1971; Lovejoy et al., 1973) were the first to estimate forces exerted on the proximal femur of early hominins during walking (Ruff, 2018). This highly influential work modelled the midstance of walking based on standing on one foot as established by Frankel and Burstein (1970) and also developed by McLeish and Charnley (1970). This model has been used repeatedly to evaluate the structural capacity of early hominin lower limb skeletal elements (e.g. Berge, 1994; Ruff, 1998). For example, the human femoral neck is unique relative to other apes in its superoinferior asymmetric distribution of cortical bone (Lovejoy, 1988; Lovejoy et al., 2002). From these principles, Ruff and Higgins (2013) argue the South African hominins *Australopithecus africanus* and *Paranthropus robustus* would have utilized a bipedal gait that required lateral sway of the trunk.

Without diminishing the importance and influence of this body of work, the limitations of this approach, although state-of-the-art at the time, should be recognized. As with all models, the estimates of forces were generated under a specific set of simplifications (assumptions) to make the problem tractable. Implicit in the single limb standing model is that midstance is sufficiently representative of the entire stance phase of the gait cycle to describe the structural demands impose by lower limb biomechanics. During standing, however, the ground reaction force (GRF) is equal to body weight, while at walking midstance, the GRF is closer to 70% of body weight because the center of mass (CoM) of the body has been accelerated upward (Richards, 2008). Second, during single limb standing, the total body CoM must be directly above the support foot in order to

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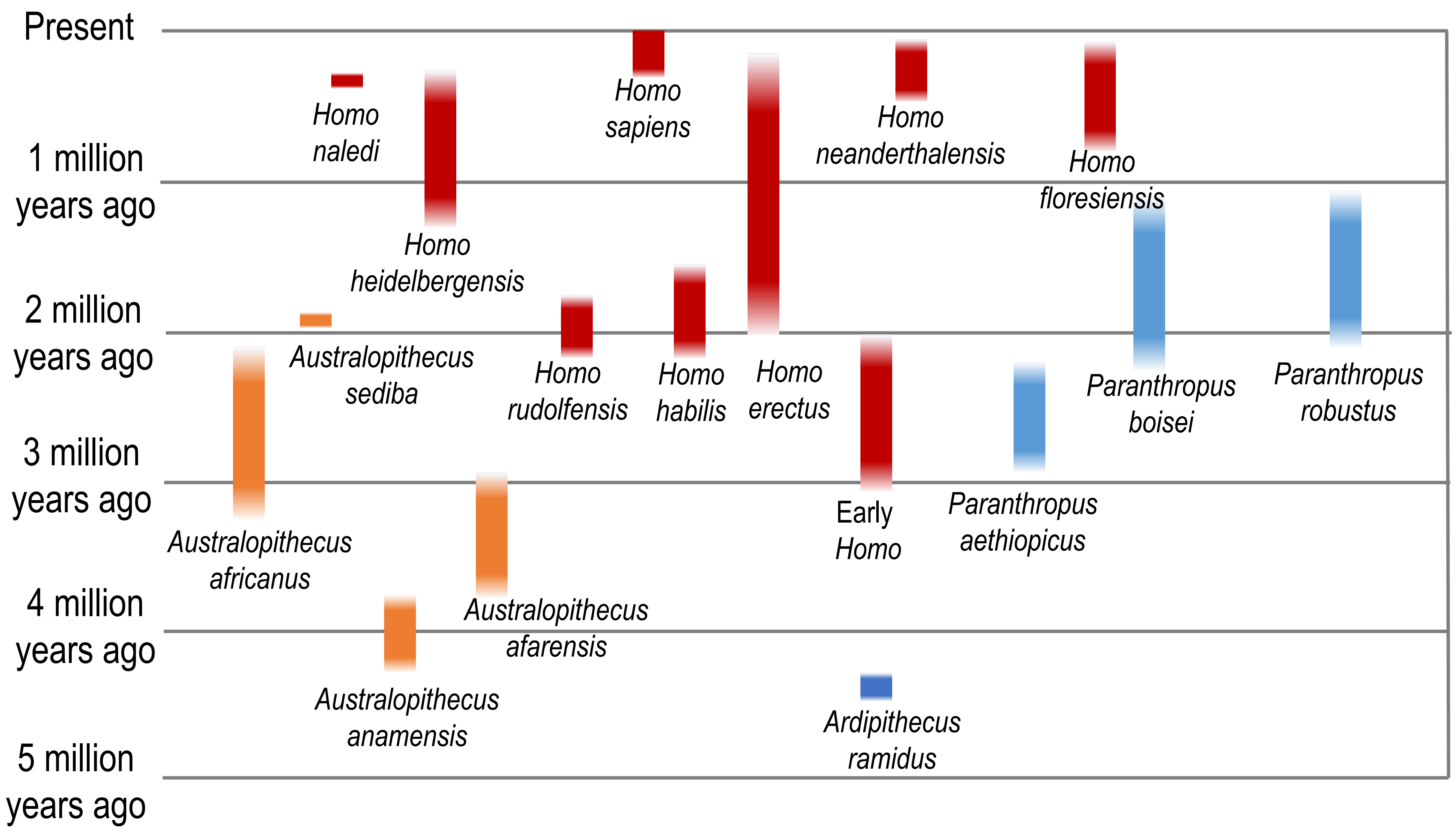
Hominin locomotion

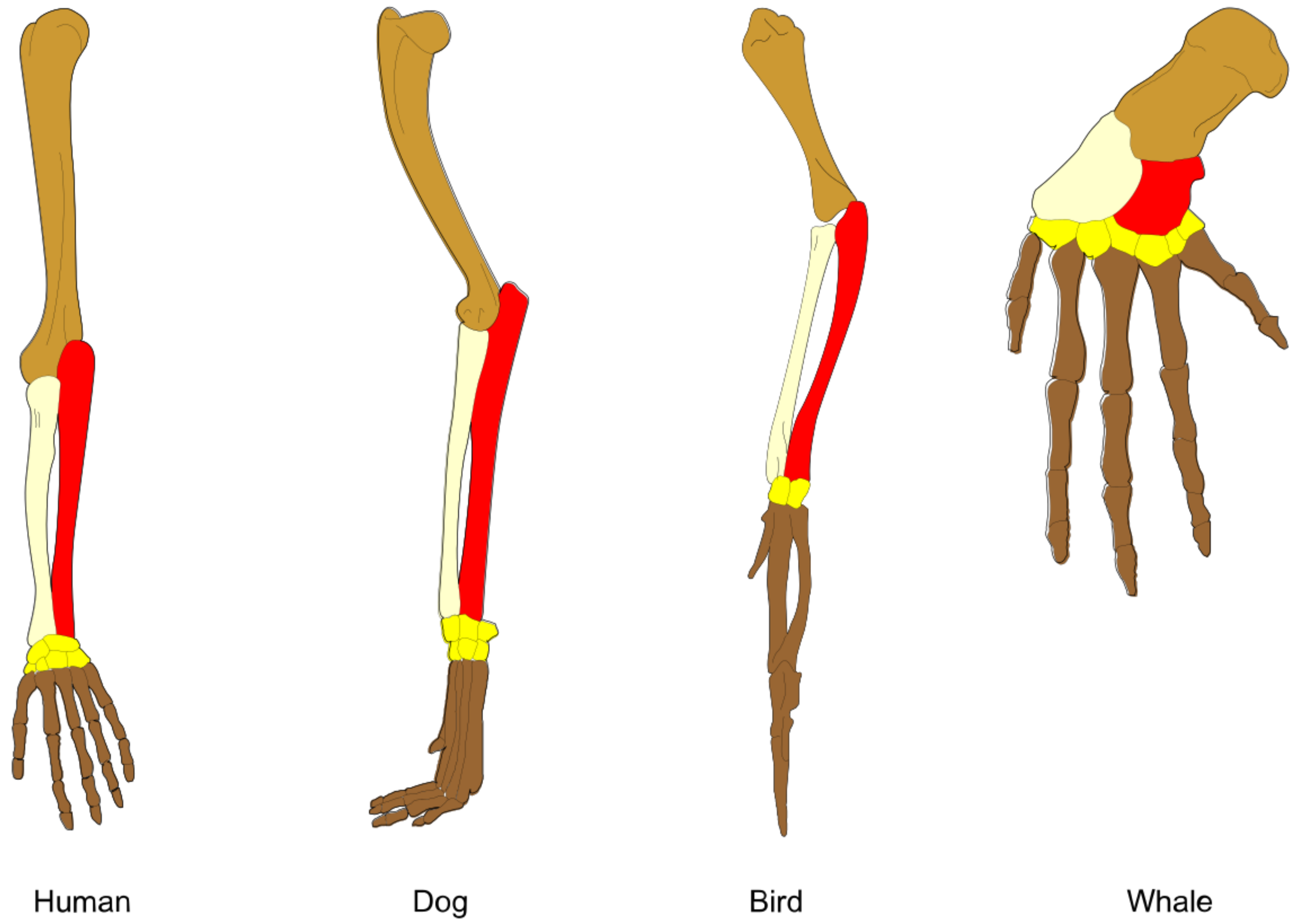


AL 288-1 “Lucy”
Australopithecus afarensis

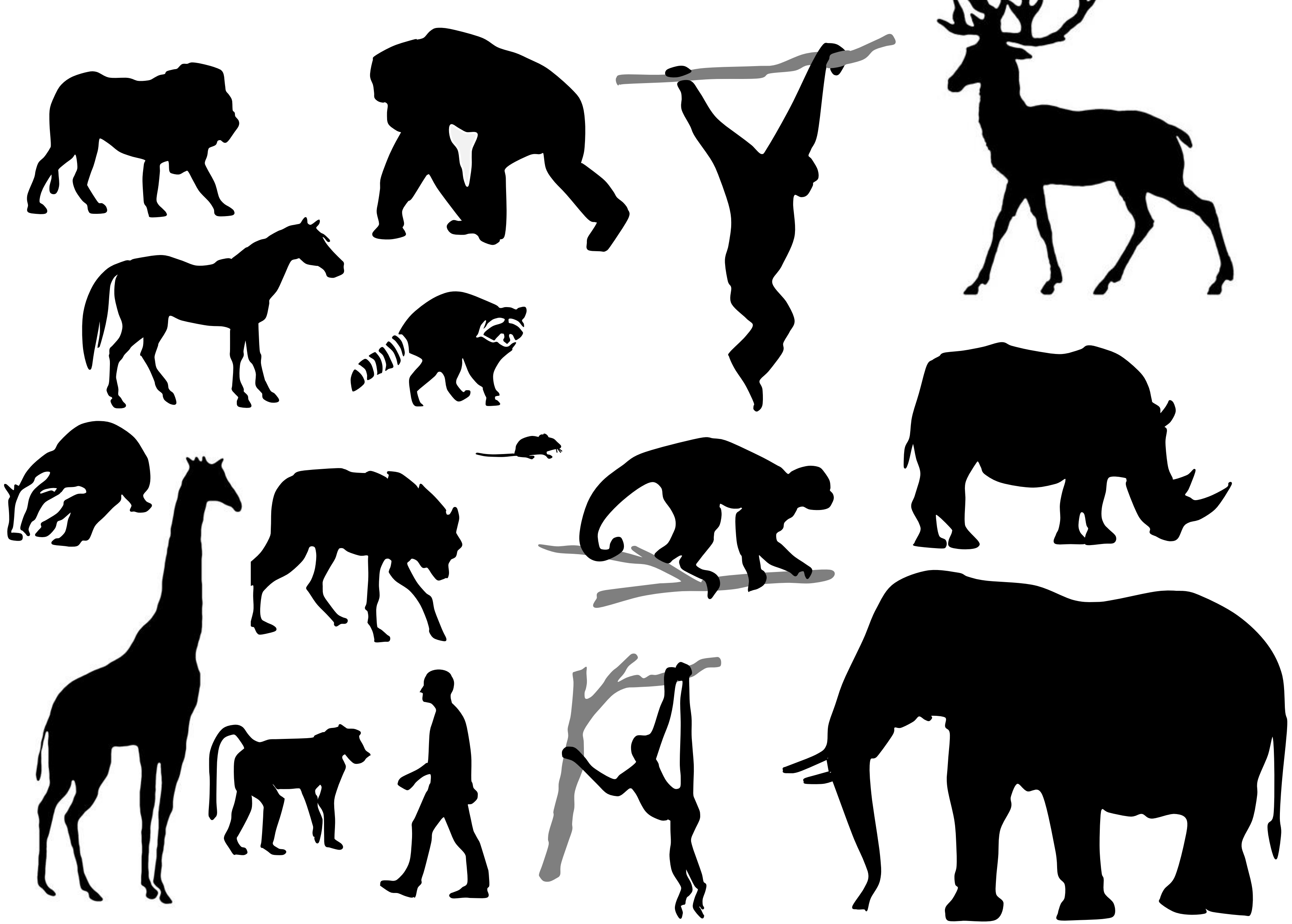
Outline

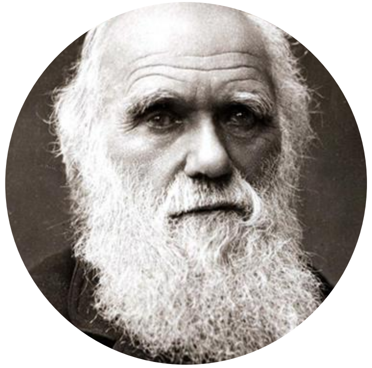
- Why invest in musculoskeletal modeling?
- An example from paleoanthropology
- Contributions from evolutionary biologists
- Some suggestions

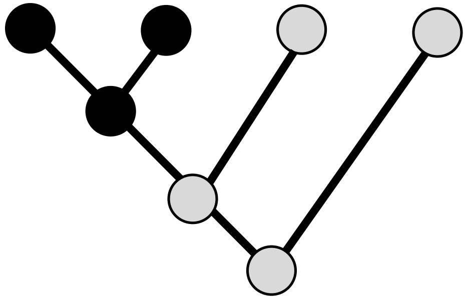
Form-Function Relationships



Form-Function Relationships



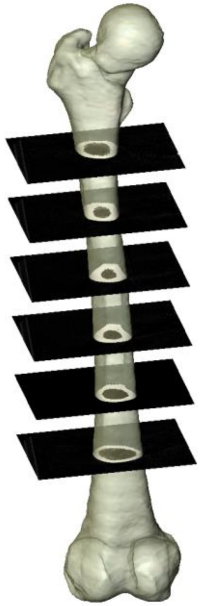


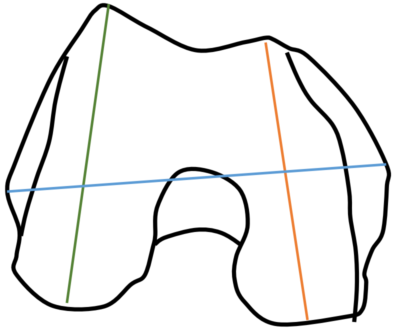


Standard Approach

Morphology

- Traditional metrics
- Cross-sectional properties
- Geometric morphometrics
- Trabecular analysis





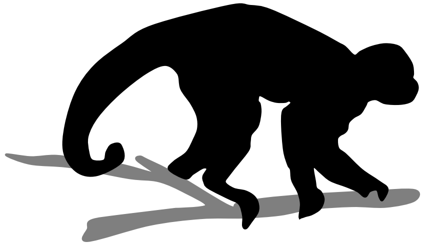
Locomotion

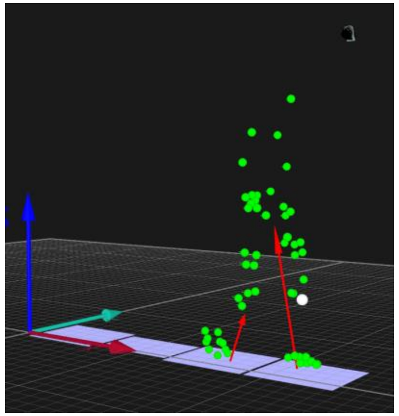
Behavior

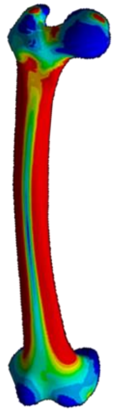
- Locomotor behavior
- Postural behavior
- Activity budget
- Substrate usage

Performance

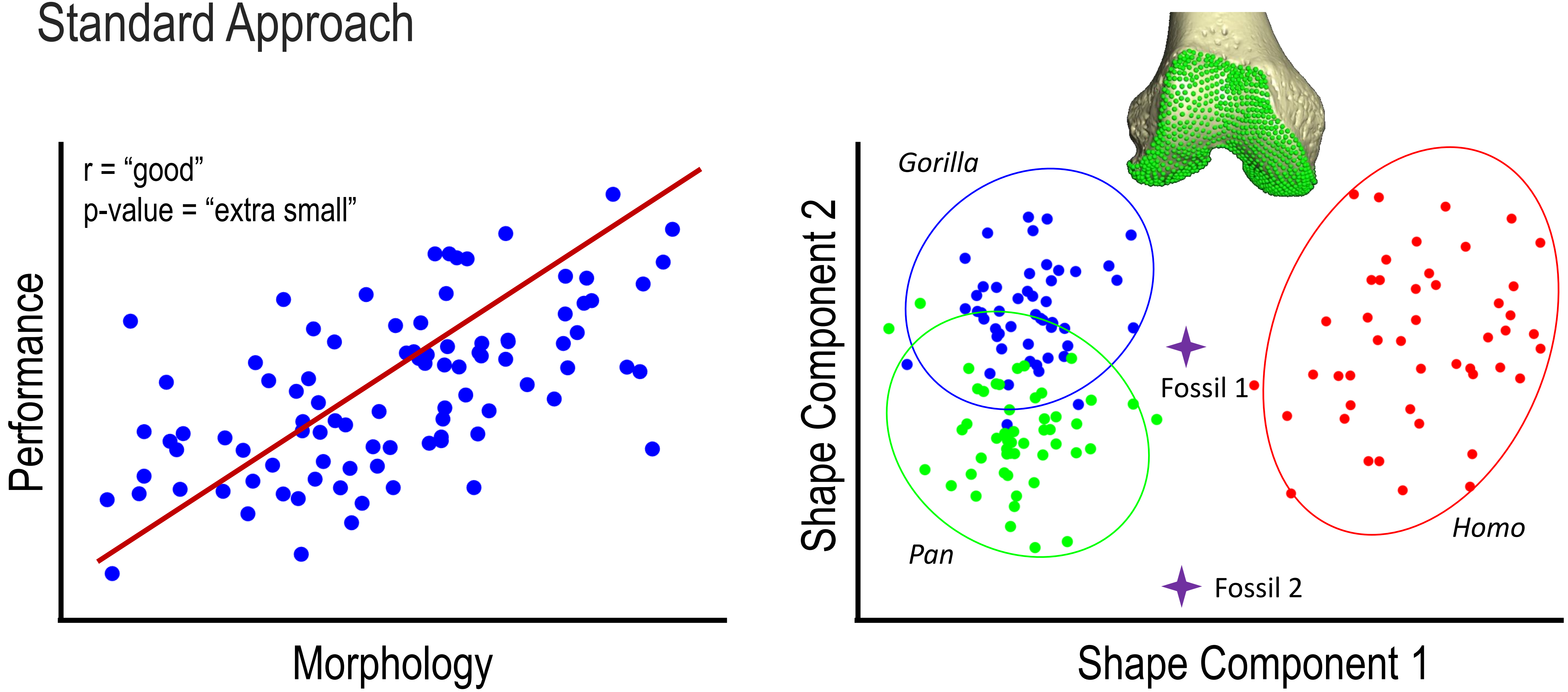
- Velocity
- Skeletal stress / strain
- Energy consumption







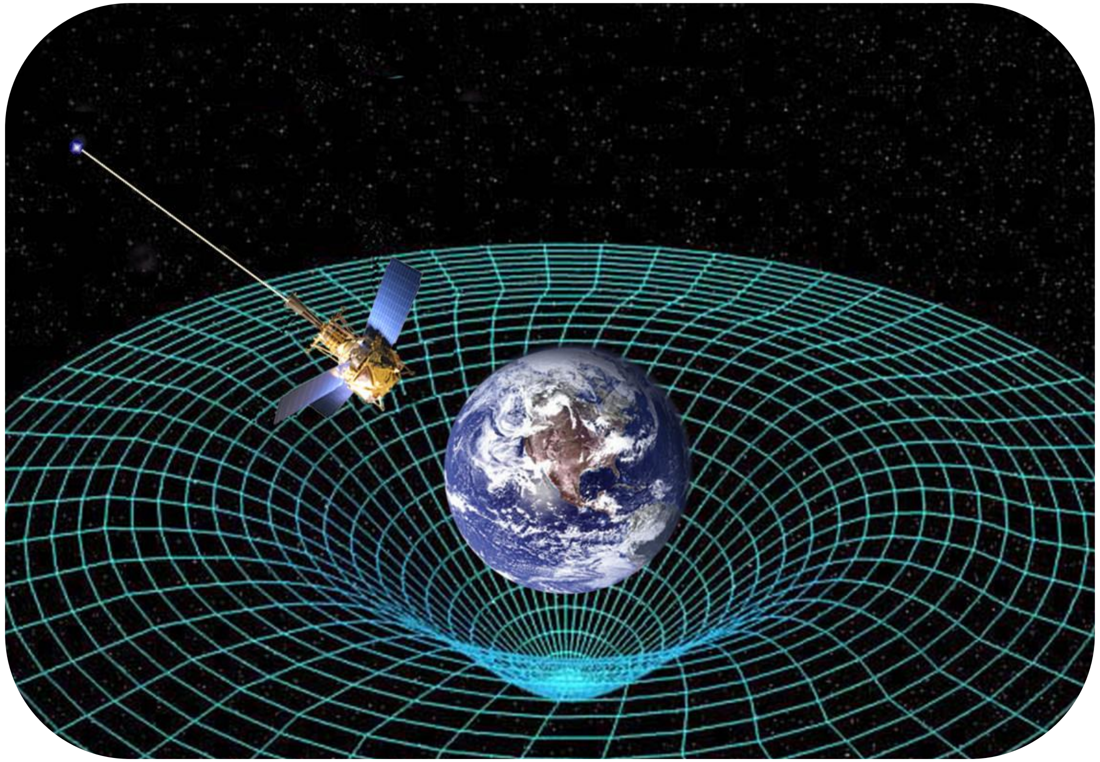
Standard Approach



Correlation is not causation

What are we asking?

$$F = \frac{Gm_1m_2}{r^2}$$



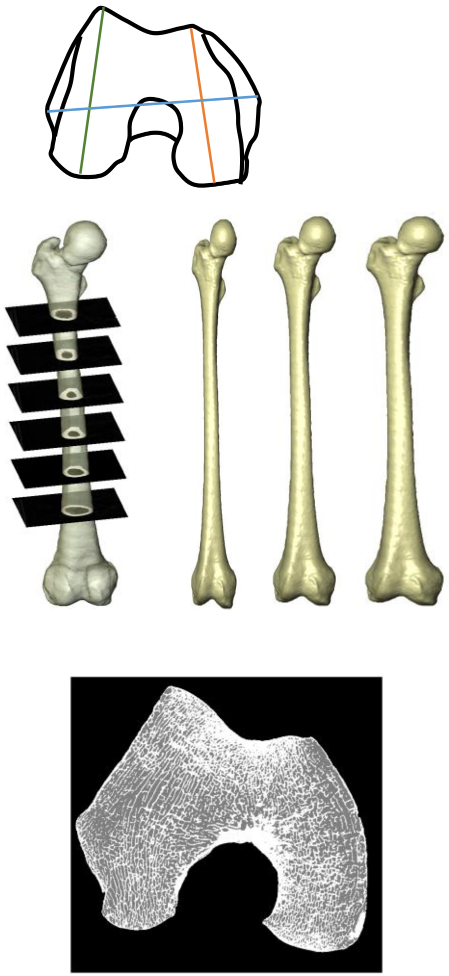
Connecting Form and Function in Locomotor Research

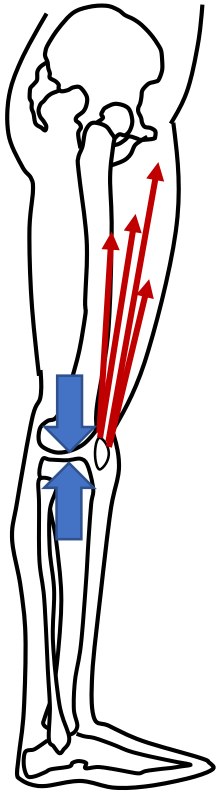
Morphology ↔ Internal Forces ↔ Locomotion

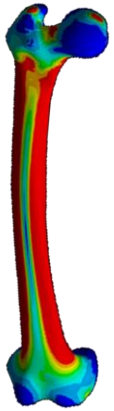
Internal Forces

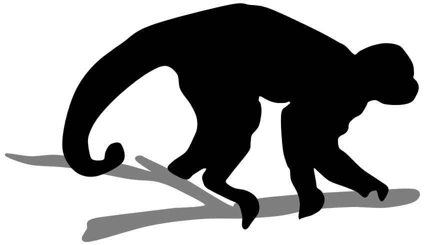
Bone-bone contact forces

Muscle forces



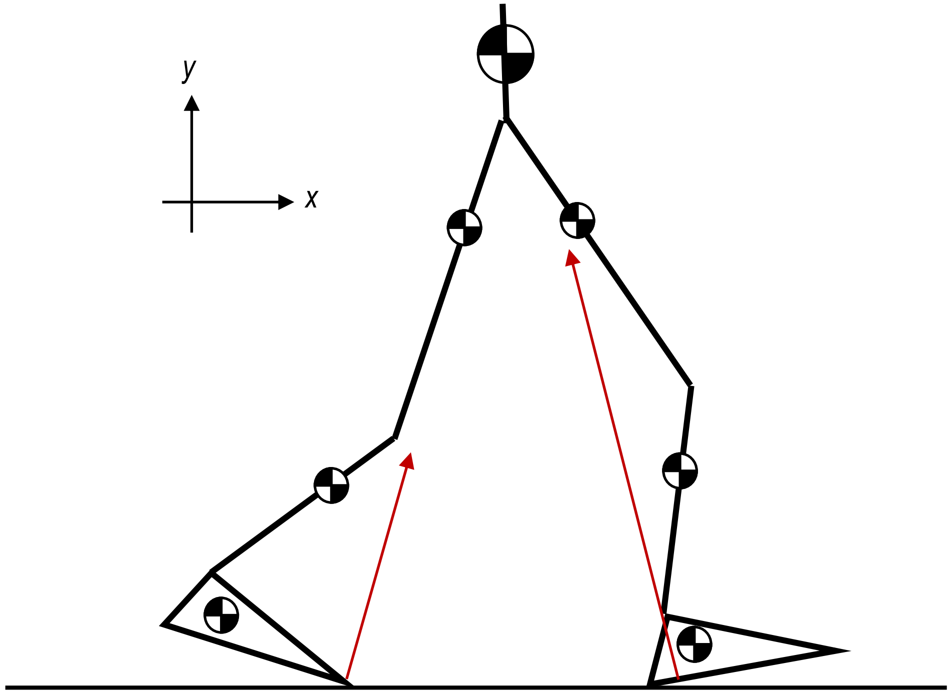




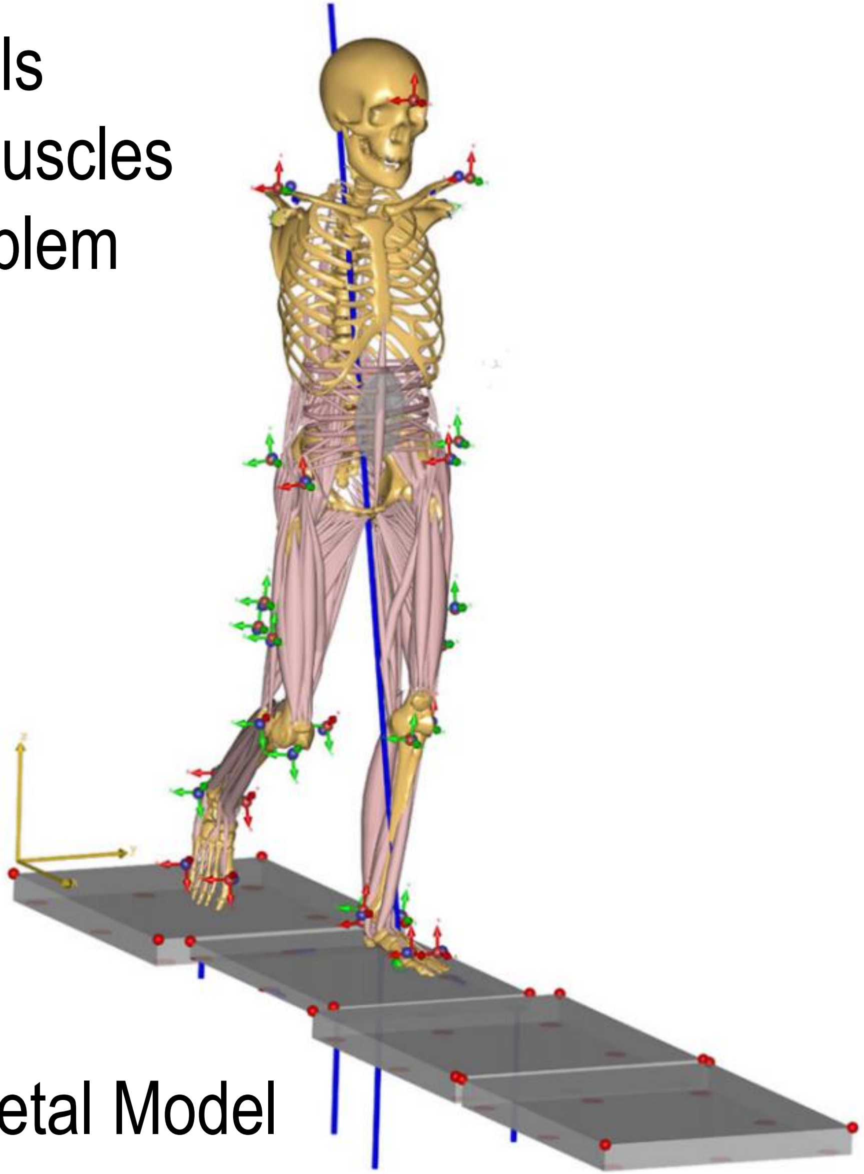


Musculoskeletal modeling

- Extends inverse dynamic models
- Includes models of individual muscles
- Solves muscle redundancy problem

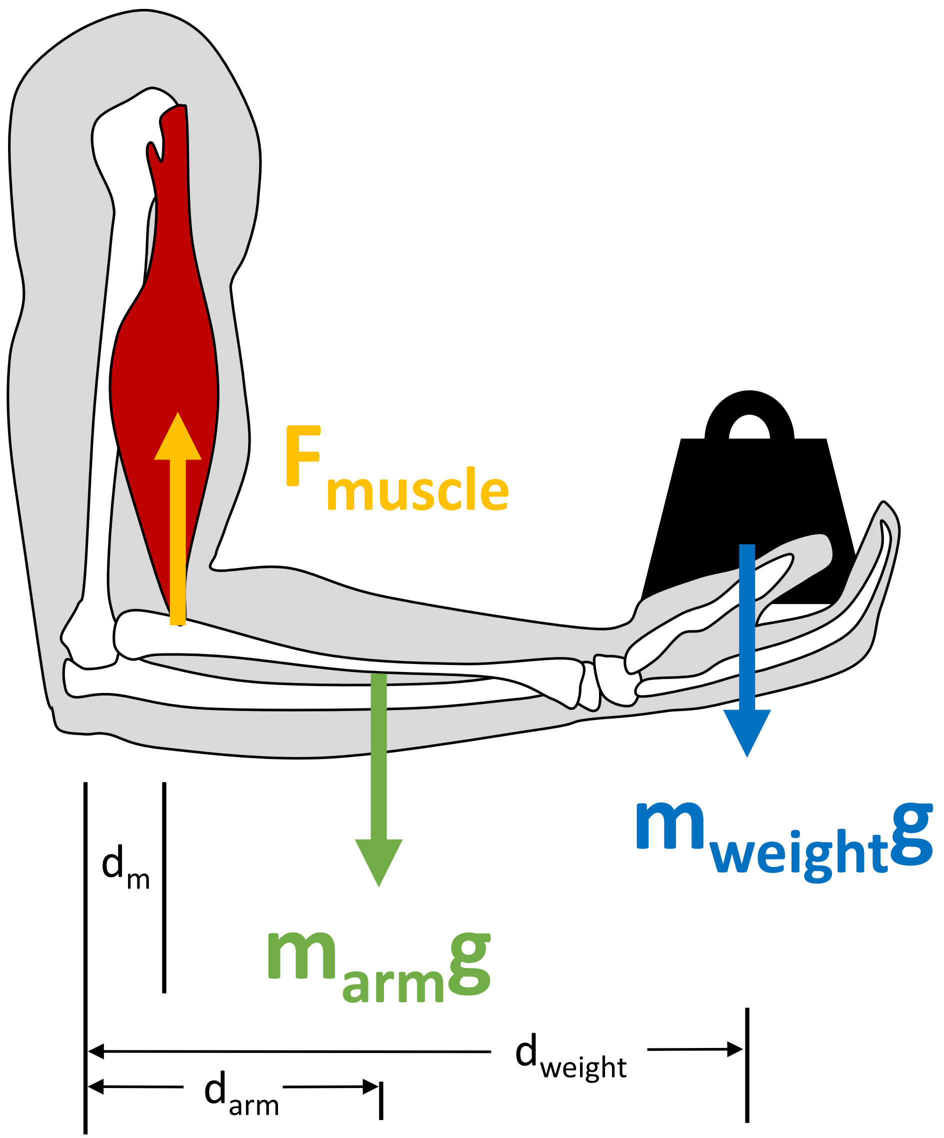


Inverse Dynamic Model



Musculoskeletal Model

Muscle redundancy problem



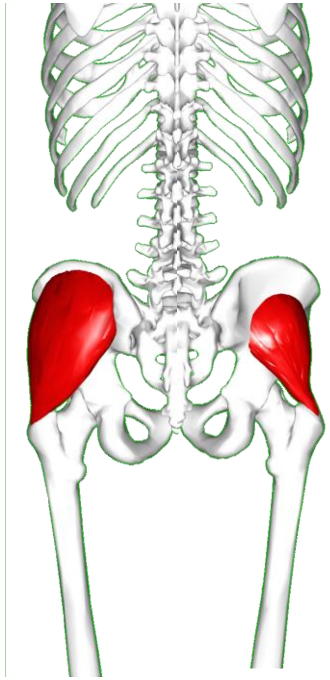
$\cancel{F_{muscle}}$

$F_{biceps\ brachii}$

$F_{brachioradialis}$

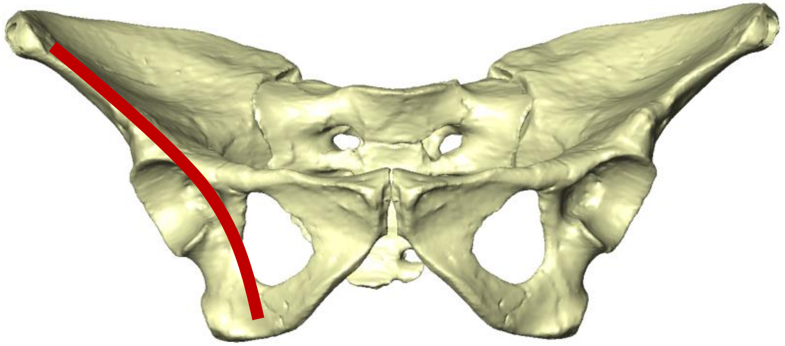
$F_{brachialis}$

Examples from Paleoanthropology

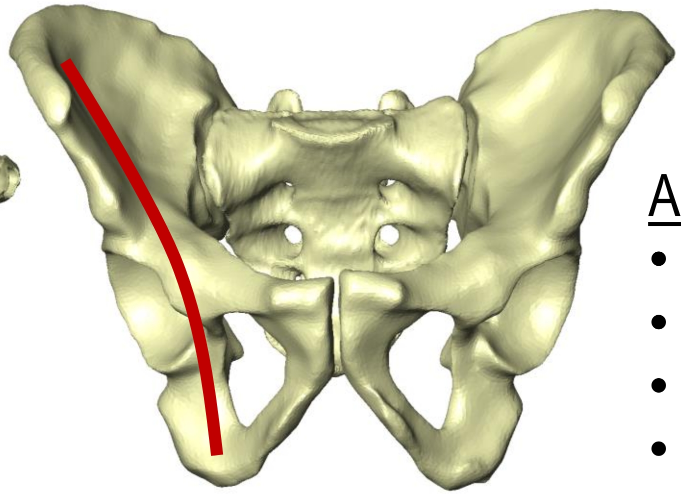


Hip abductor mechanism

Gluteus medius muscle
Gluteus minimus muscle
Stabilizes pelvis / trunk



Australopithecus afarensis

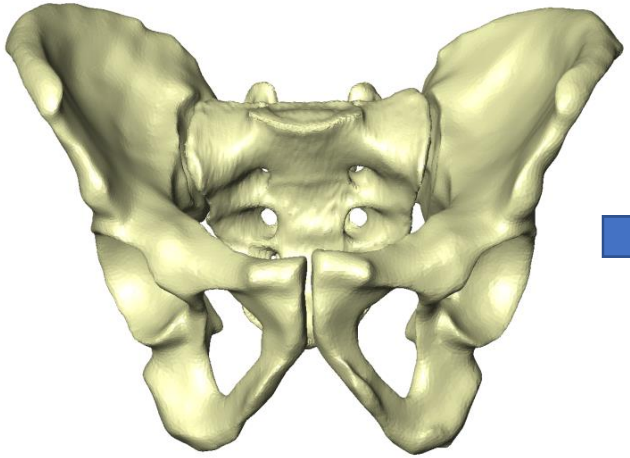


Modern human

<u>Australopithecine Bipedalism</u>

- Modern bipedalism
- Less efficient
- Hip / knee flexion
- Lateral trunk sway

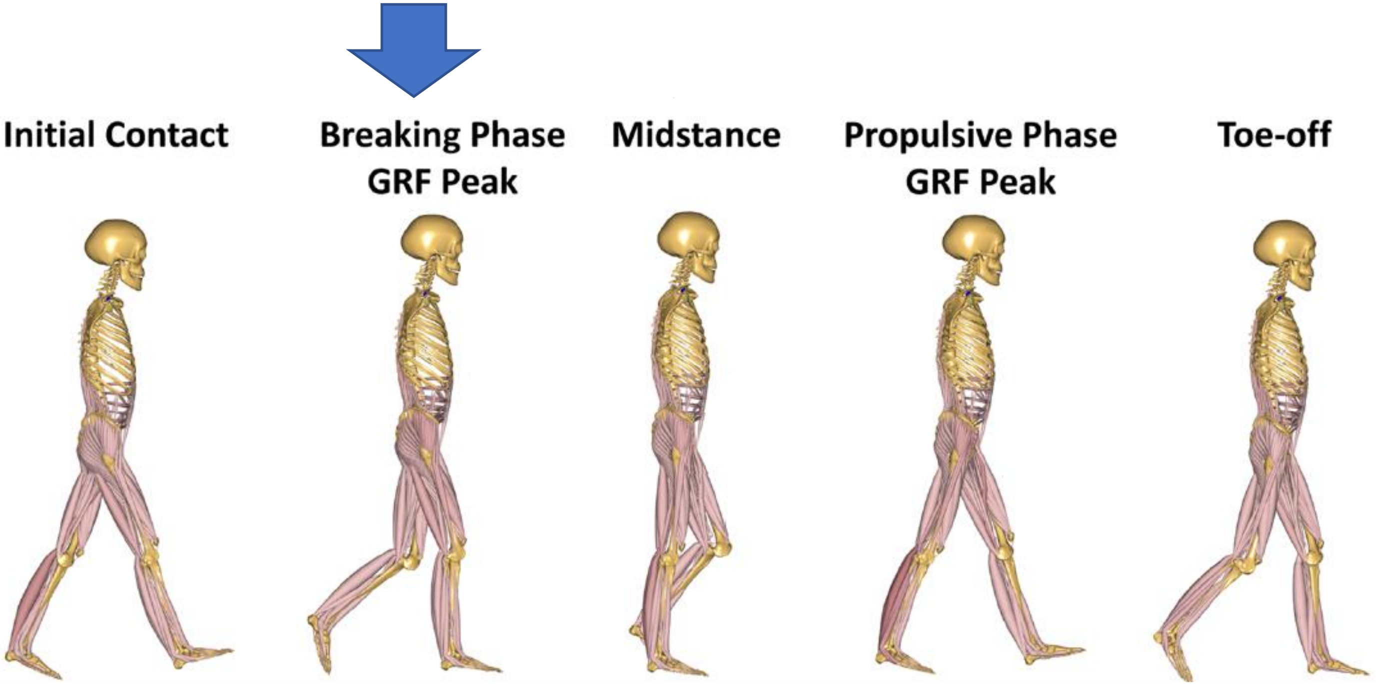
<u>Locomotion</u>
Narrow pelvis

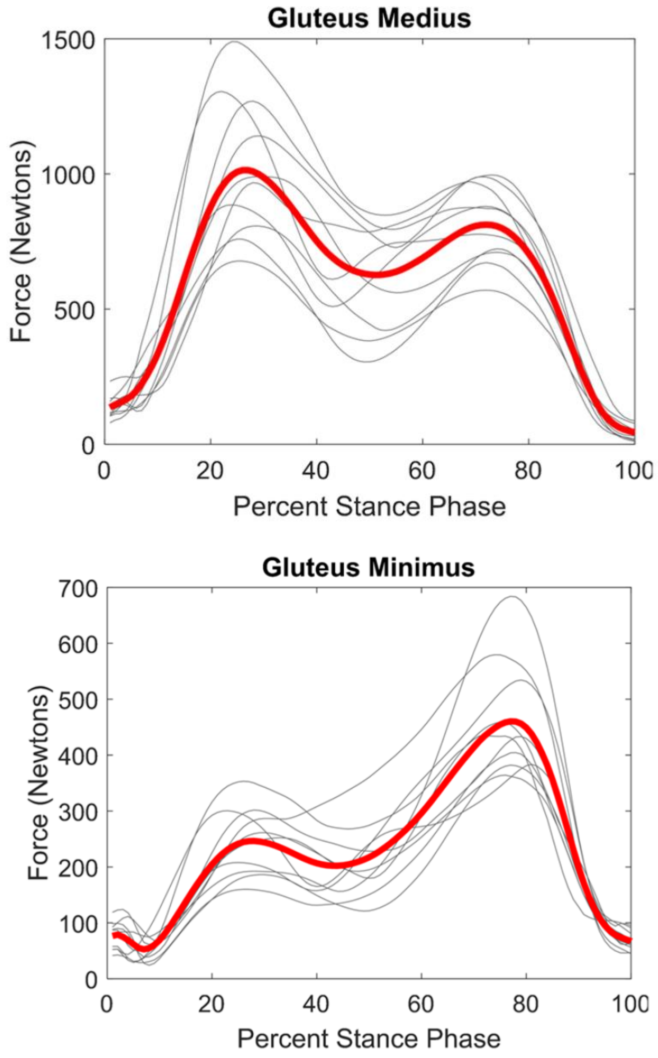


Modern human

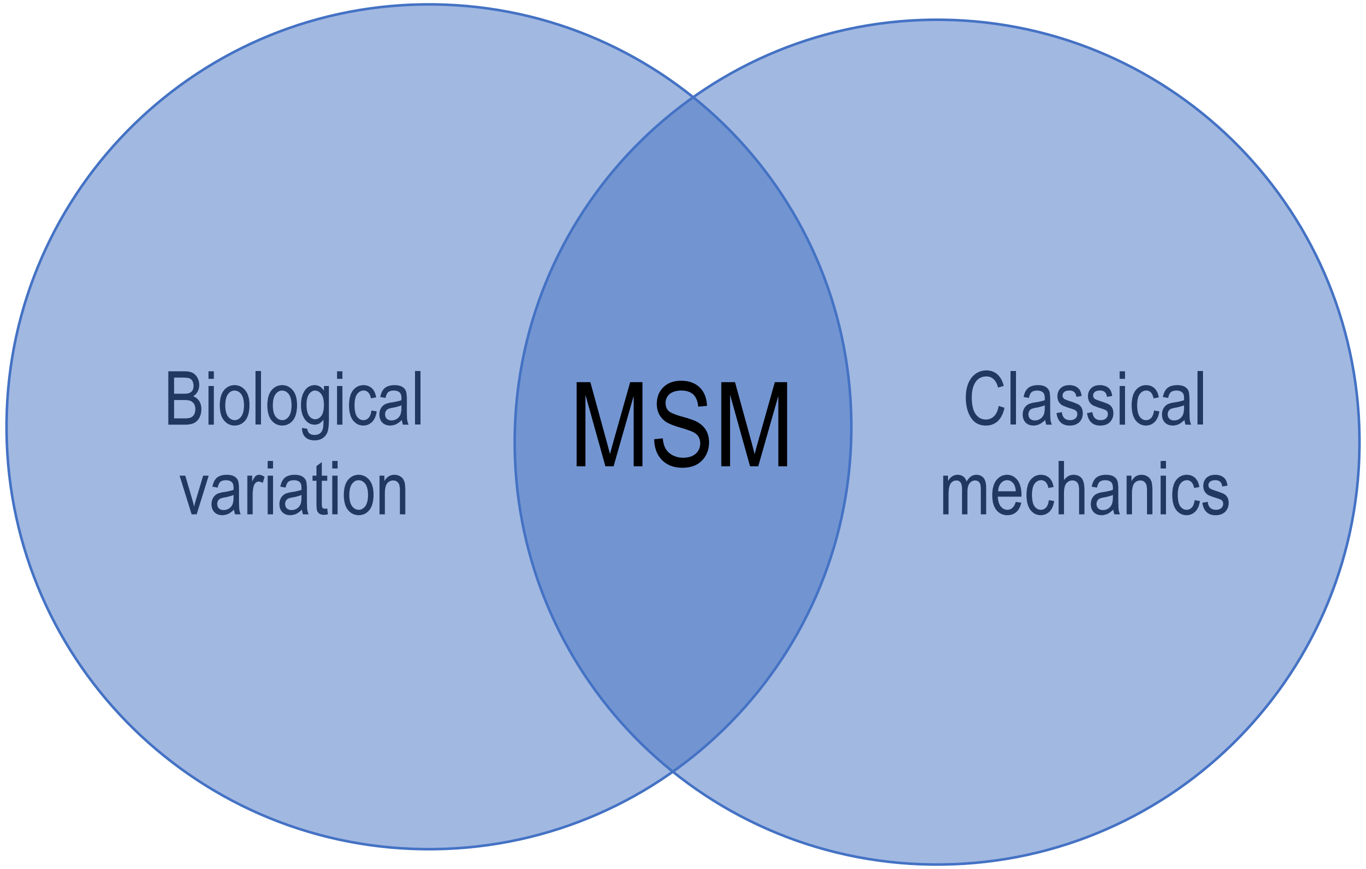
<u>Obstetrics</u>
Wide pelvis

Examples from Paleoanthropology





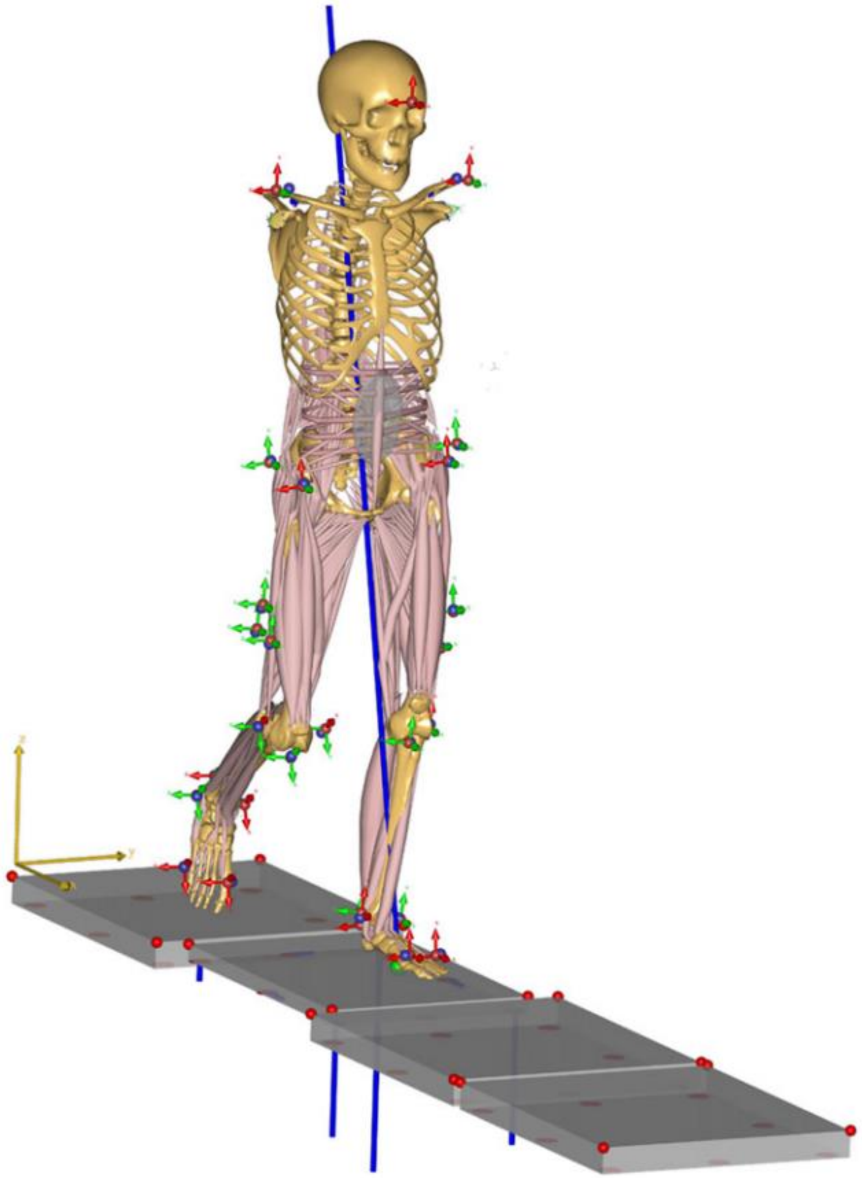
Contributions from evolutionary biologists



- Skeletal Variation
- Muscle Variation
- Models of other animals

Suggestions for starting MSM

- More accessible than ever
- Models are abstractions
- There are many choices



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University of Tennessee

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Sylvester AD, Lautzenheiser SG, Kramer PA. 2021. Muscle forces and the demands of human walking. Biology Open 10, bio058595. doi:10.1242/bio.058595

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  - **Simulation based Conceptual Exoskeleton Design** by Professor of Biomechanics John Rasmussen from Aalborg University

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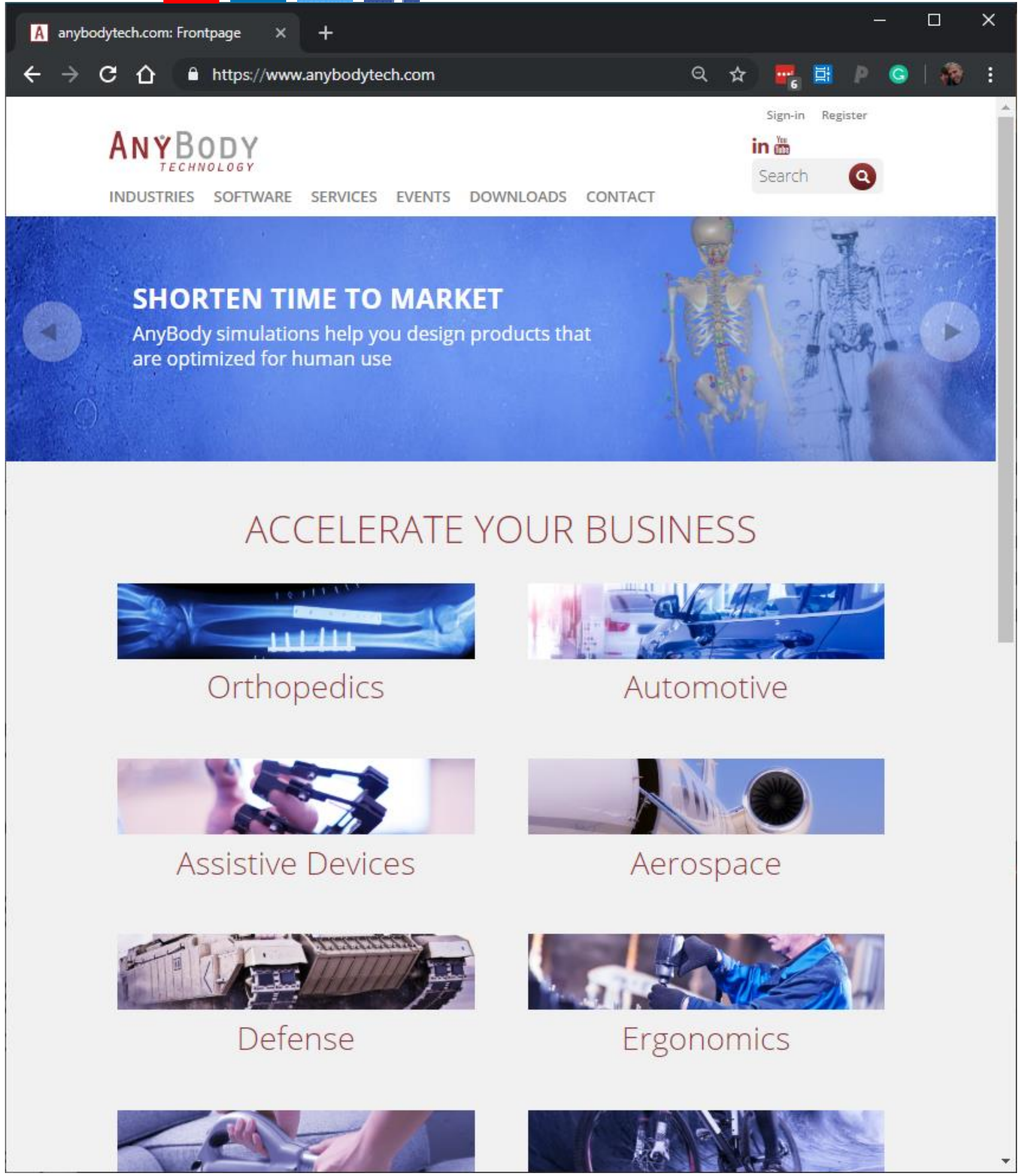

Thank you for your attention
- Time for questions