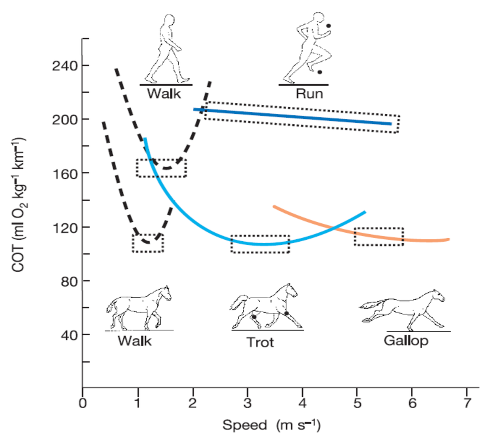
Engineering
University at Buffalo The State University of New York
The School of Engineering and Applied Sciences
MECHANICAL AND AEROSPACE ENGINEERING DEPT.

Musculoskeletal Simulation-based Parametric Study of Optimal Gait Frequency in Biped Locomotion

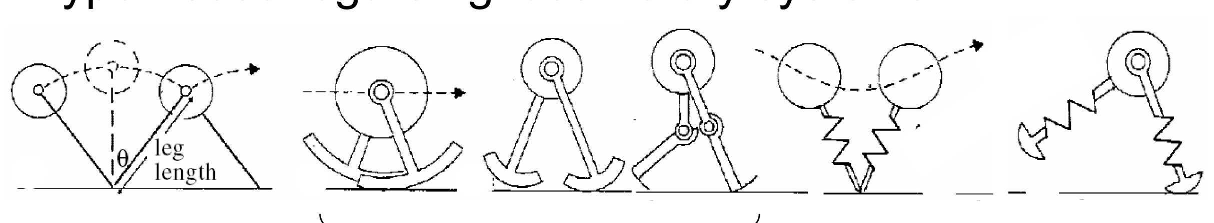
HYPOTHESIS



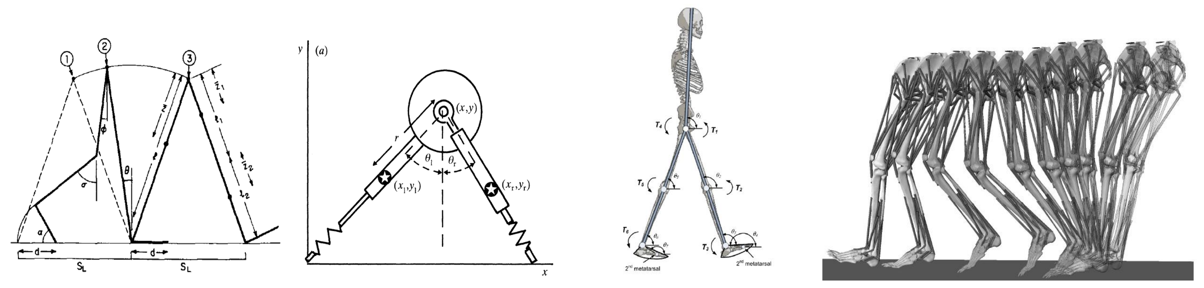
- Expended effort is minimal when the locomotory appendages/ propulsive structures are moving at steady-state in periodic gaits at their resonant frequencies.

MOTIVATION

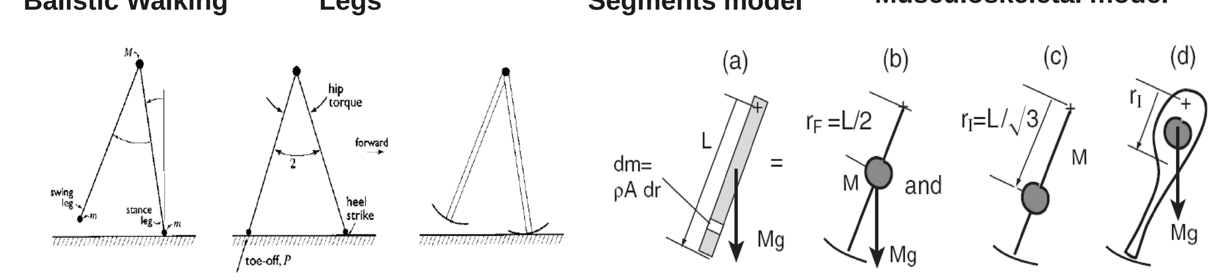
- Obtaining insights that will allow for better design of the robotic systems.
- Using virtual computational tools for studying hypotheses regarding locomotory systems.



Alexander's (1979) Walking Model; McGeer's (1990) Walking Models; Blickhan (1989), McMahon (1990); McGeer (1990)



Mochon & McMahon's (1979) Balistic Walking; Alexander's (1992) Compliant Legs; Ren, Jones, & Howard (2007) 7-Segments model; Foster's (2003) Musculoskeletal model



Kuo's (2001) Idealized Simplest model, Simplest model, and Anthropomorphic model; Ahlborn's (2006) Pendulum models

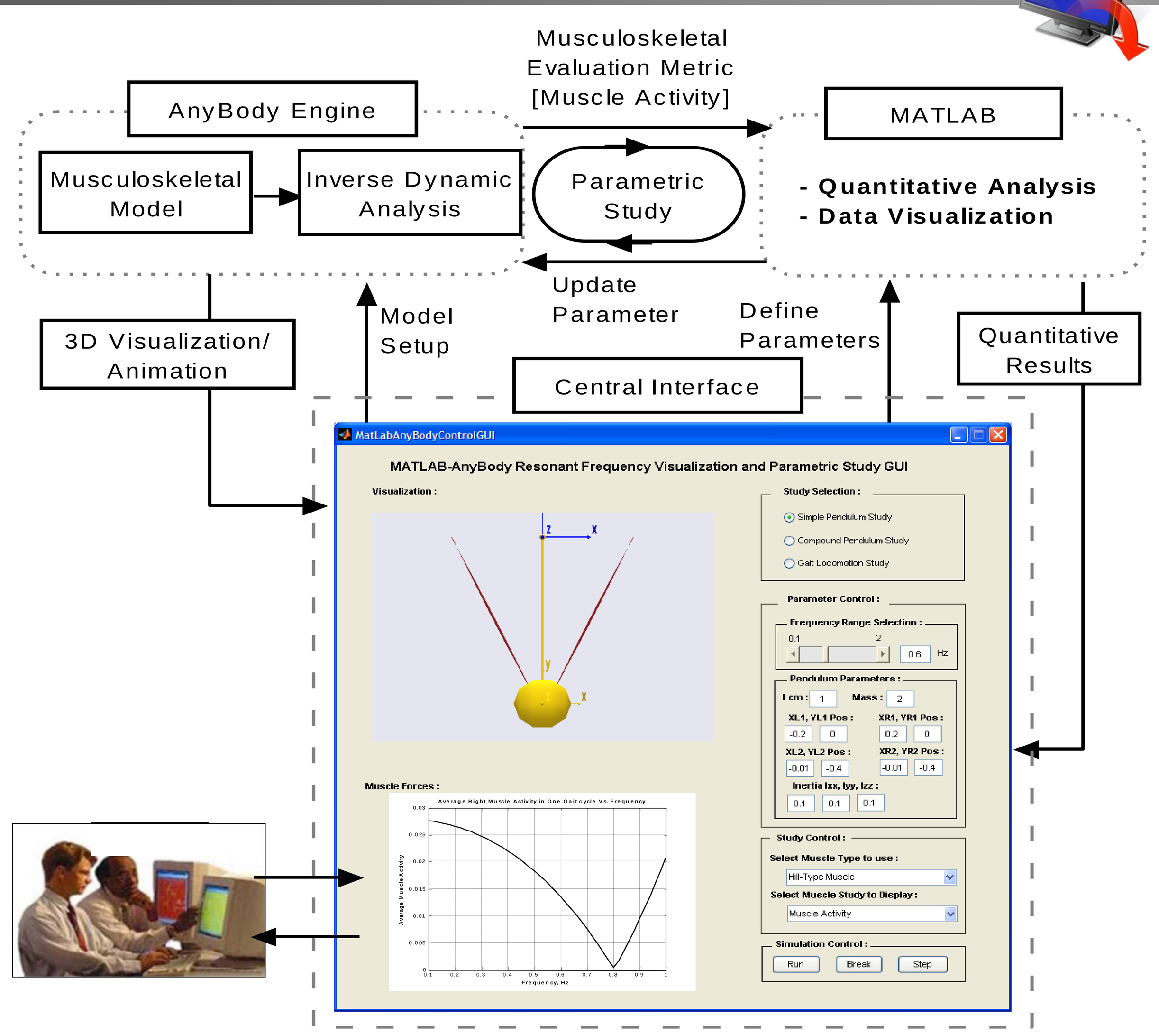
RESEARCH QUESTIONS

- Can a musculoskeletal simulation system predict system resonance frequencies?
- If so, how well does the result compare with analytical solutions?
- Can we simulate and predict preferred walking frequency Using musculoskeletal simulation?

OUR APPROACH

- Create, test, and evaluate the hypothesis using a Virtual Prototyping (VP) methodology (also known as Simulation-Based Design).
- Perform comparative parametric studies of biped locomotion models (with varying level of complexity) completely in a virtual environment.
- Combine engineering support tools, such as musculoskeletal analysis and parametric sweeps, within an integrated environment to allow monitoring of internal variables (such as muscle forces and muscle activities).

ANALYSIS FRAMEWORK



Analysis framework: A MATLAB GUI serve as a Center Interface that allows performance studies of walking in response to various inputs. The AnyBody engine provides the computational musculoskeletal modeling while the parametric sweeps and plotting are handled by MATLAB.

CASE STUDIES

Three case studies :

(1) Simple Pendulum;
(2) Compound Pendulum;
(3) 18-DOF Lower Extremity Musculoskeletal Model.

- Both simple and compound pendulum models have been used as a simplified lower extremity model to predict human stride frequency, with some success [2];
- To gain insights to the more complex musculoskeletal model;

Natural Frequency of 'pendulum like' model:

$$\omega = \frac{n}{2\pi}\sqrt{\frac{g}{L}}$$

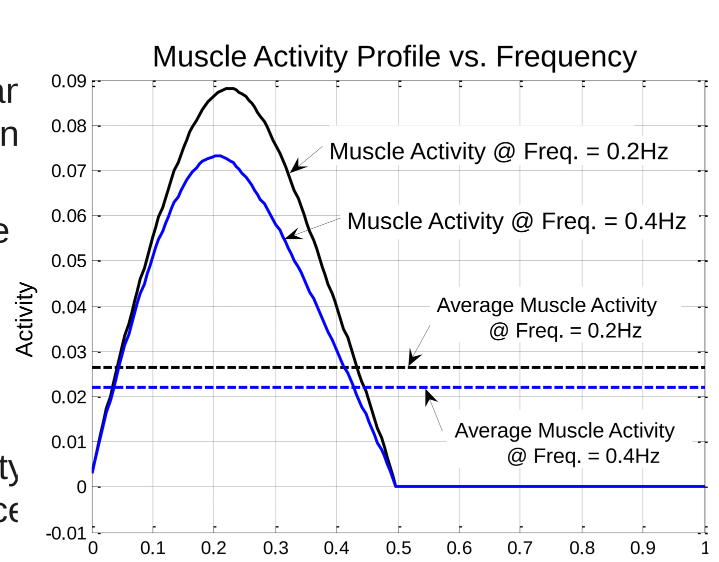
$n=\sqrt{3/2}=1.225$ - Uniform rod;

$n=\sqrt{5/2}=1.581$ - Cone shape;

- In previous studies [2], researchers have shown $n=\sqrt{2}=1.414$ correlates well with the human preferred walking speed;
- We compare this with our musculoskeletal simulation results.

Evaluation Metric:

- Muscle energy expenditure measurements: Electromyograr (EMG) or Oxygen Consumption
- Studies have shown they correlate well to predict muscle usage;
- AnyBody muscle activity correlates well with EMG data.
- Average muscle activity, the average value of muscle activity profile is used as a performance measure.



CASE STUDY I – SIMPLE PENDULUM

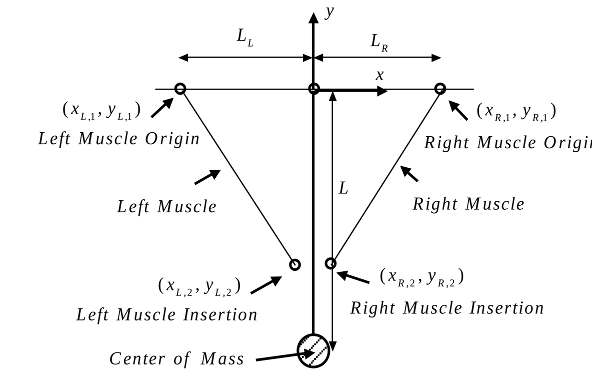
Natural Frequency, ω of Simple Pendulum:

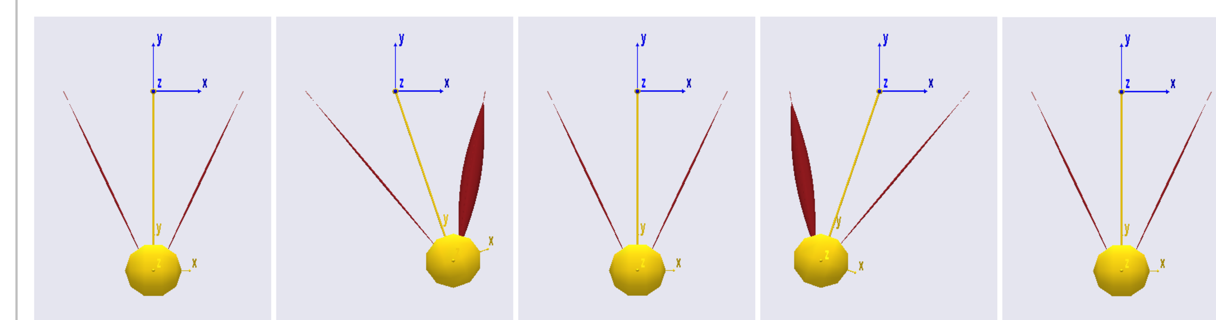
$$\omega = \frac{1}{2\pi}\sqrt{\frac{g}{L_{CM}}}$$

For $L_{CM}=0.4m$ - distance to center of mass;
$g=9.81m/s$ - gravitational acceleration;
$\omega=0.788Hz$

Musculoskeletal Simulation:

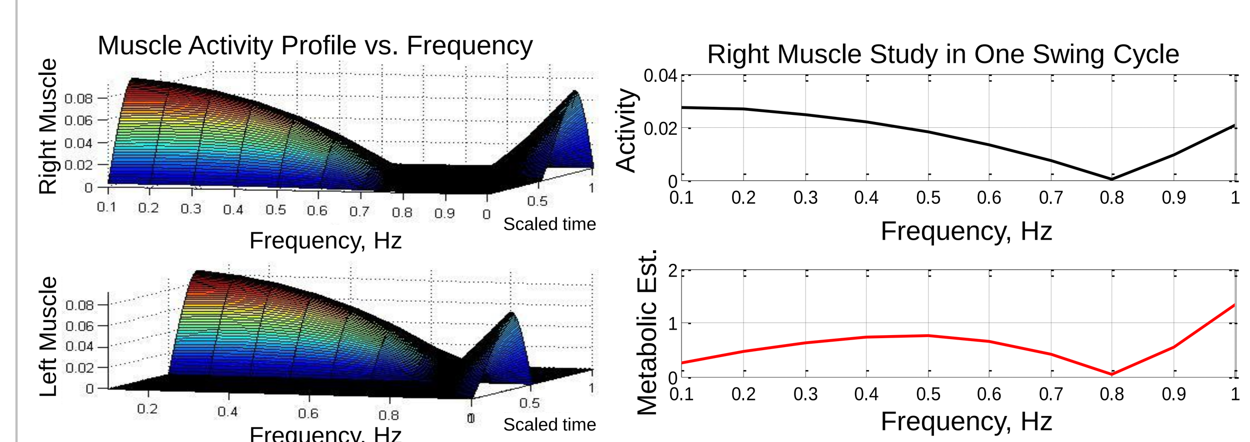
- Two Hill-Type muscles;
- Rotate at rate: $\theta = 20^{\circ}\sin(\omega t)$
- ω varied from 0.1Hz – 10Hz;
- Complete a swing cycle shown.





Results:

- Muscle activity profile across frequency range 0.1Hz – 10Hz ;
- There appear to have a 'cut-off' frequency where activity is minimum;
- To locate this minimum, we plot the average muscle activity vs. Freq.;
- The frequency where minimum muscle activity occurs is 0.79Hz.



Analytical Solution: 0.788Hz.
Musculoskeletal Simulation: 0.79Hz.

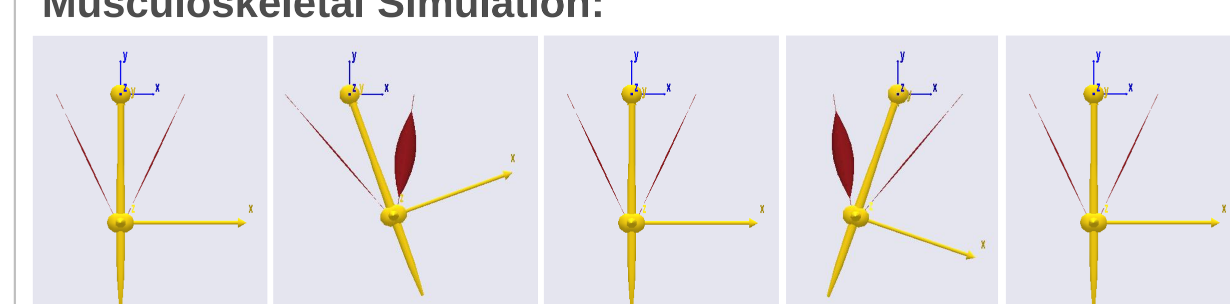
CASE STUDY II – COMPOUND PENDULUM

Natural Frequency, ω of Compound Pendulum (Rod):

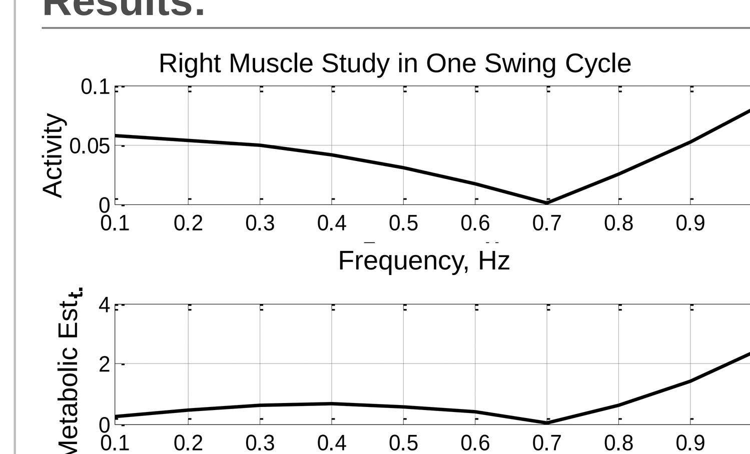
$$\omega = \frac{1}{2\pi}\sqrt{\frac{3g}{2L}}$$

For $L=0.8m$ - length of uniform rod;
$g=9.81m/s$ - gravitational acceleration;
$\omega=0.6825Hz$

Musculoskeletal Simulation:



Results:



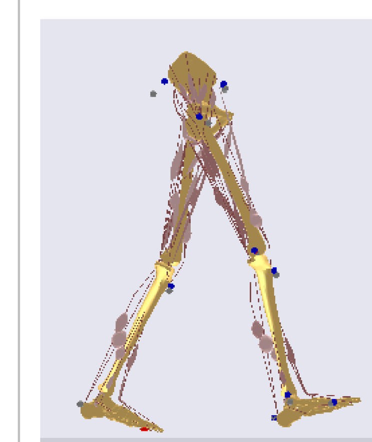
Analytical Solution: 0.683Hz.

Musculoskeletal Simulation: 0.69Hz.

CASE STUDY III – LOWER EXTREMITY

Human Gait:

- Gait of "Normal Man":
  - Stride Frequency – 0.77Hz
  - Stride Period – 1.3 seconds
  - Stride Length – 1.28 m
  - Speed – 0.99m/s
- Maintain 'normal walking' up to 3m/s
- Variance in 'natural' walking speed:
  - Village (0.8m/s) vs. Cities (1.7m/s)
  - Long vs. Short walkway
  - Treadmill vs. Natural surfaces
  - Indoor vs. Outdoor
- 'Walk-run' transition: 1.92m/s

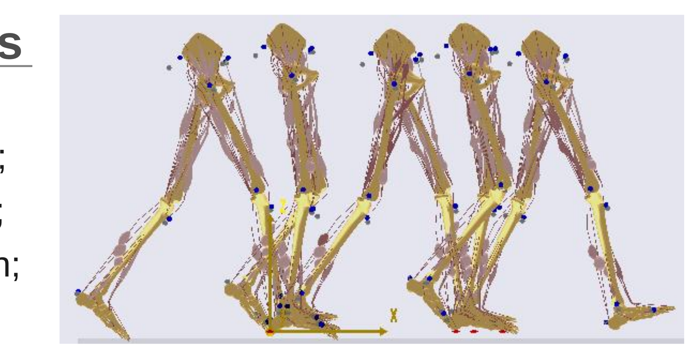


Musculoskeletal Model:

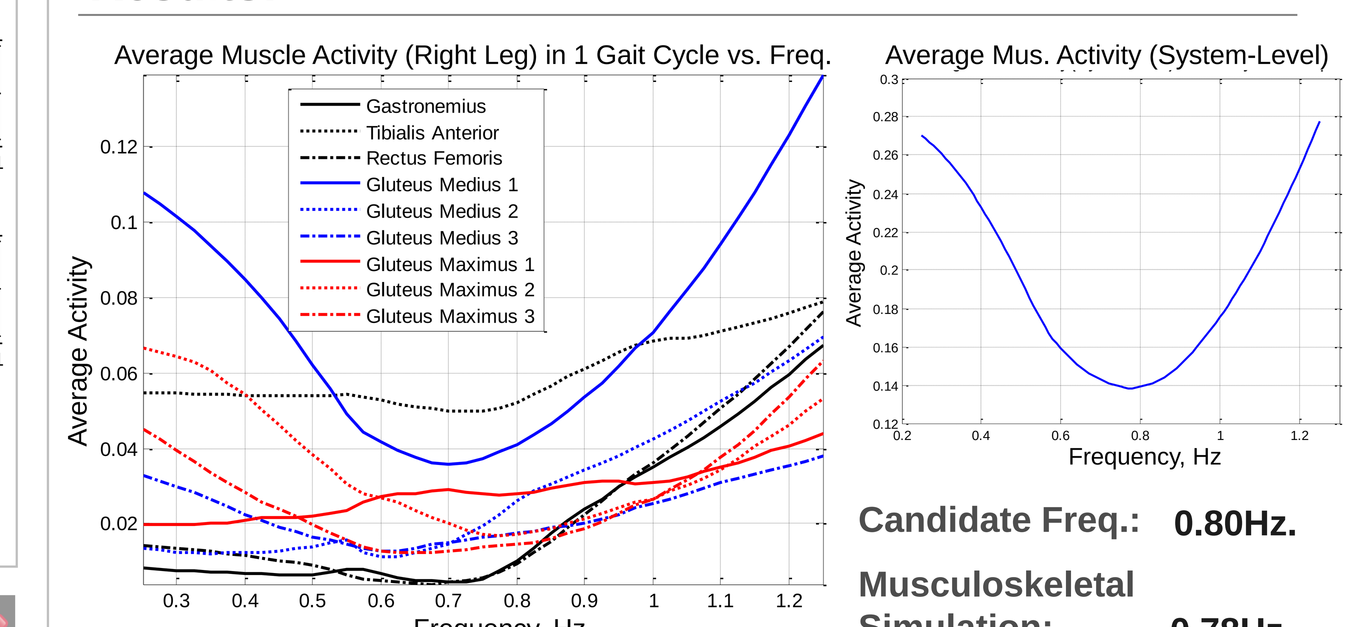
- Available in AnyBody Model Repository [3];
- 7 rigid bodies (Thigh x 2 + Shank x 2 + Foot x 2 + Pelvis)
- 27 unique muscles in each leg (54 in total)
- 18 Degree-of-Freedom
- Length: Thigh (0.44m), Shank (0.44m), Foot (0.22m)
- Hill-type muscle model
- Driven by motion capture data (1.25 seconds/cycle)

Simulation Settings

- Using the 'Man' data set from [4];
- Range of speed: 0.3 m/s – 1.5 m/s;
- Not consider force & moment data;
- Assuming the data sets are smooth;
- The candidate walk at 0.8Hz.



Results:

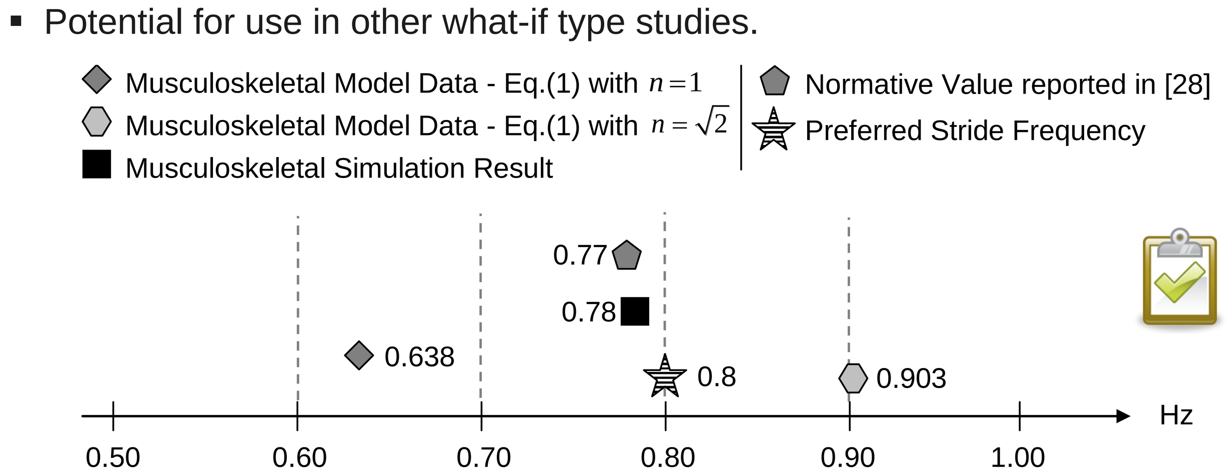


Candidate Freq.: 0.80Hz.

Musculoskeletal Simulation: 0.78Hz.

Conclusion:

- The musculoskeletal simulation shows that the system used least effort (minimum activity) at 0.78Hz.
- Closer prediction of the preferred stride frequency (0.80Hz) compare to using equations in [2] ;
- Potential for use in other what-if type studies.



REFERENCE

[1] Lee, L-F, and Krovi, V. "Musculoskeletal Simulation of Optimal Gait Frequency in Biped and Human Locomotion," Proceeding of IEEE BIOROB 2008, Scottsdale, Arizona, October 19-22, 2008.

[2] K. G. Holt, J. Hamill, and R. O. Andres, "The Force-Driven Harmonic Oscillator As A Model For Human Locomotion," Human Movement Science, vol. 9, pp. 55-68, 1990.

[3] AnyBody Technology Group, The AnyScript Model Repository version 6.0, 2006, Available for download at: http://anybody.aau.dk/repository/.

[4] C. L. Vaughan, B. L. Davis, and J. C. O'Connor, "Biomechanical Data Resources," Human Kinetics Publishers, 1999.

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