SYSTEMATIC FORCE PATTERN PRODUCED BY MUSCLE COORDINATION IN HUMAN STANDING

KIERAN NICHOLS

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Introduction to Kieran

- Originally from Trinidad and Tobago
- Whenever I’m not at lab, I’m at the gymnastics
- Food enthusiast

Mechanical terms to Know

- ***F***: the force of the ground on the feet
- **x**: anterior, **z** is superior (sagittal plane)
- ***Force* ratio**: F_x / F_z
- **Center of Pressure** (xCP): location of application of the vertical component of F
- **Center of Mass** (x,zCM): the weighted average position of the masses of all segments in a body
- **Whole Body Angular Position** (WBAP): the weighted average orientation of the segments of the body

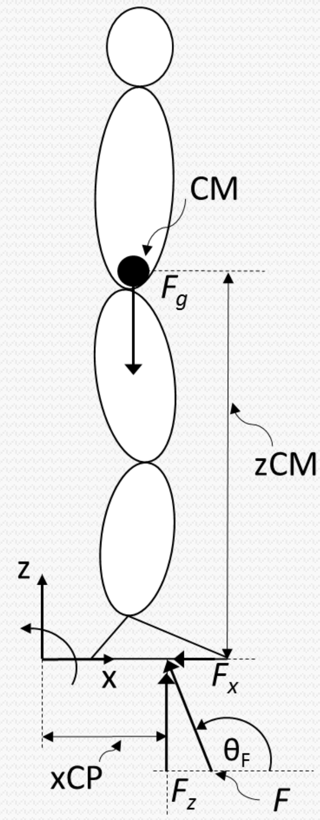


Figure 1: Reference frame and key variables

Thesis

- This thesis aims to further the understanding of how humans maintain upright posture in unperturbed standing, as expressed in variation patterns in the force of the ground on the feet

Mechanical Requirements of Unperturbed Standing

- All segments of body within 30 deg of vertical
- Average translation and rotational velocity is 0
- Avg. $F_z = F_g$
- Avg. $F_x = 0$
- Avg. $T_{CM} = 0$

Standing Models

- Single Inverted Pendulum (SIP)
- Double Inverted Pendulum (DIP)
- Triple Inverted Pendulum (TIP)
- Intersection Point (IP) control

Single Inverted Pendulum

- Model proposes balance control is controlled by x_{CP}-$x_{CM} \propto a_{xCM}$
- Ankle torque controlling rotational motion through an effective stiffness from simple rotational spring
- Other studies showed the intrinsic ankle stiffness was not large enough to maintain passive SIP control

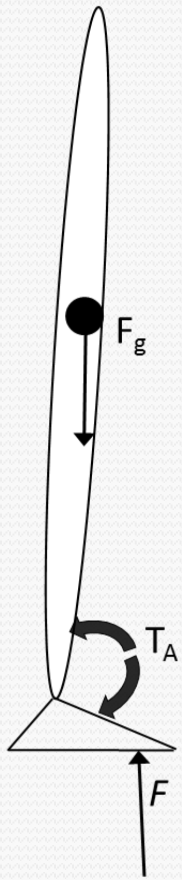
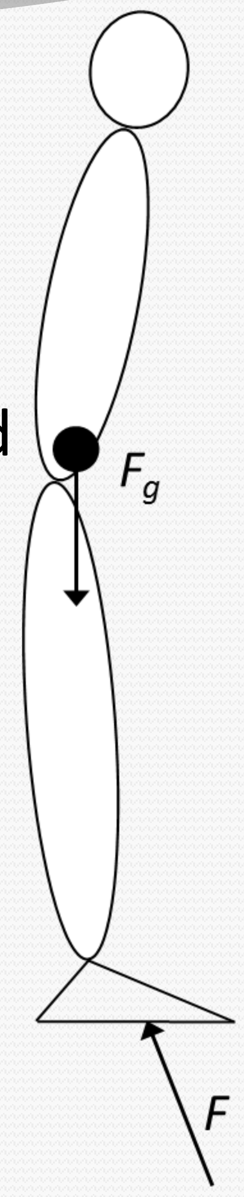


Figure 2 showing the SIP model with T_a being the ankle torque.

Double Inverted Pendulum

- Segmented body into legs and torso
- Contained two eigenfrequencies that approximated the upper and lower limits of Fx power spectrum
- Able to achieve stable coordination using hip joint and no ankle torque



Triple Inverted Pendulum

- Segmented into torso, upper, and lower legs
- Able to replicate mechanical eigenfrequencies from 0.1 to 20 Hz.
- Low ankle stiffness was possible when coupled with active hip torque

Intersection Point Control

- They showed that the forces of the ground on feet are directed at a fixed point located **above the center of mass** when joints above the ankle were held rigid for an anthropomorphic mechanical model.
- These forces are instead directed at a fixed point **near the knee** when the hip and knee torques are held constant

Intersection Point Control

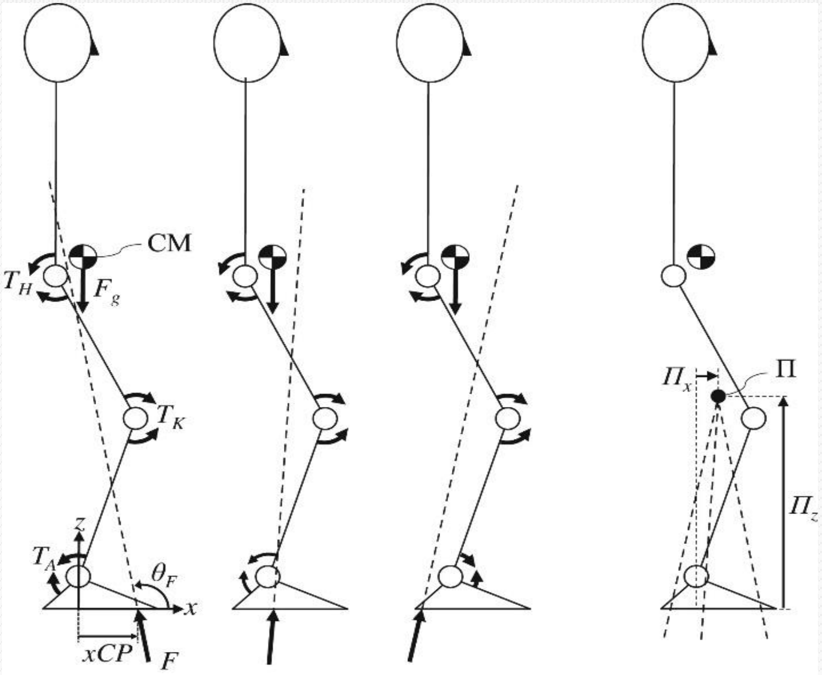
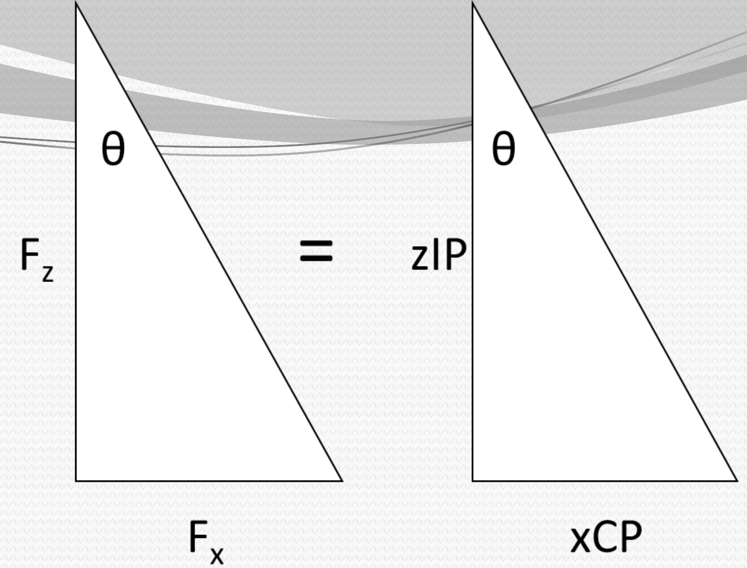


Figure 3 from Gruben & Boehm, 2012 shows the variation of xCP and F_x/F_z to create an IP near the knee when hip and knee torques are held constant. T_h, T_k, and T_a are the hip, knee, and ankle torque respectively. Π is the location of the Posture Specific Intersection Point

Connection of Previous Research to Thesis

- The pendulum models (SIP, DIP, TIP) offer insight into how simple mechanical models can be used to represent standing balance control
- The model proposed by Gruben and Boehm proposed *F* variation strategies by which the neural system could coordinate translational and rotational balance.
- The proposed strategies could be a means by which humans maintain the upright posture.

Intersection Point Theory



- If there is a linear relationship between xCP and F_x/F_z then the F will intersect at a point (Gruben & Boehm, 2012).
- zIP = xCP / (F_x/F_z) where the constant zIP is the height of the IP.
- This geometric relationship will occur when xCP and F_x/F_z are in phase with one another, meaning that an instantaneous increase of xCP is simultaneous with an increase of F_x/F_z.

Intersection Point Theory

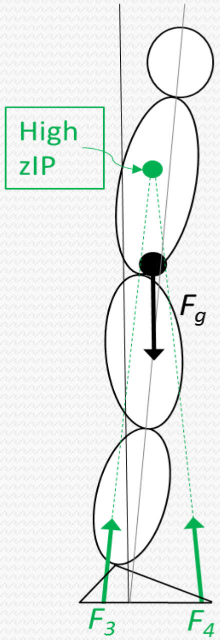


Figure 4 shows an example of a high zIP

- If a F_4 (F_x to the left, F_z up) has an IP above a body's zCM (Fig. 4)
  - it will cause the body to have a translational acceleration to the left
    - counter-clockwise angular acceleration which act to restore upright posture.

Intersection Point Theory

- If a F_2 (Fx to the left, Fz up) has an IP below a body's zCM (Fig. 5), it will cause the body to have a translational acceleration to the left as before but will have a clockwise angular acceleration

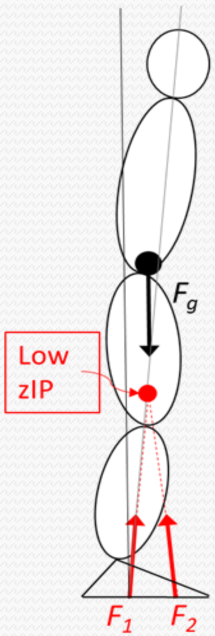


Figure 5 shows an example of a low zIP

- This motion combination acts to reposition the CM back to the desired upright posture position
- but also acts to rotate the whole body further in the direction of the initial postural perturbation.

Purpose of Thesis

- to investigate the presence of IP behavior in unperturbed standing by analyzing how xCP and F_x/F_z covary across time.

Hypothesis

- there will be a significant presence of IP behavior (at least 30% of trial time) which will be identified by the time intervals where
  - xCP and F_x/F_z are both above an absolute minimum threshold (0.0001 m and unitless respectively)
  - are in phase with one another (within +5 and -5 degrees).

Significance

- This potential IP control can be used for humanoid robotic control and the improvement of control systems for prostheses
- Alterations in IP control may provide insight into the balance disruption associated with neuromuscular diseases such as stroke and Parkinson’s disease

Focus of Method

- A Wavelet Analysis (WA) of F_x/F_z and xCP will be performed on unperturbed standing of twenty healthy individuals that is recorded on a calibrated custom force plate.

Force Plate

- Rigid aluminum plate
- 7 uniaxially loaded force sensors
- Sensors individually calibrated to relate its voltage to known forces
- CP determined using geometry of sensor locations and force magnitudes
- Error assessment of Fx, Fz, and xCP

Experimental Method

- Twenty healthy adults will stand for 50s
- Stood on force plate, relaxed and upright with their arms at their side
- Looked towards a X mark on paper at head height

Wavelet Analysis (WA)

- This method is used due to the non-stationary nature of the signals.
- It gives a description of the frequency changes throughout the time data.
- The outputs are amplitude and phase for a given frequency and time.
- zIP is obtained by dividing the magnitudes of the xCP by F_x/F_z for each particular time and frequency.

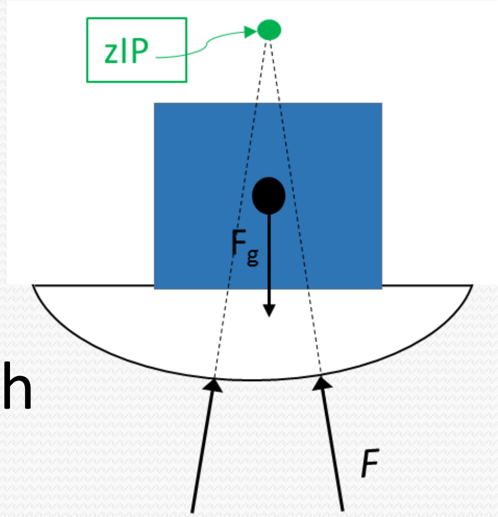
What will WA give?

- zIP is obtained by dividing the magnitudes of the xCP by F_x/F_z for each particular time and frequency.
- Magnitude in each of the signals is above 0.0001 (m for xCP and unitless for F_x/F_z) and the phase difference of xCP and F_x/F_z is close to 0 (within 5 degrees)
- For the selected zIP, the average of all IP heights at each 0.2 Hz increment will be calculated from 0.2 to 10 Hz.

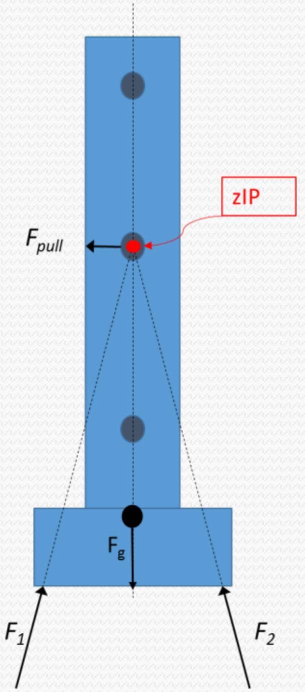
Key characteristics to investigate

- How the height of IP changes with frequency
- The potential time localized occurrences of IP
- The possibility of IPs that are in phase and out of phase
- The percentage of time there is IP control in each trial.

Validation of WA and Force Plate



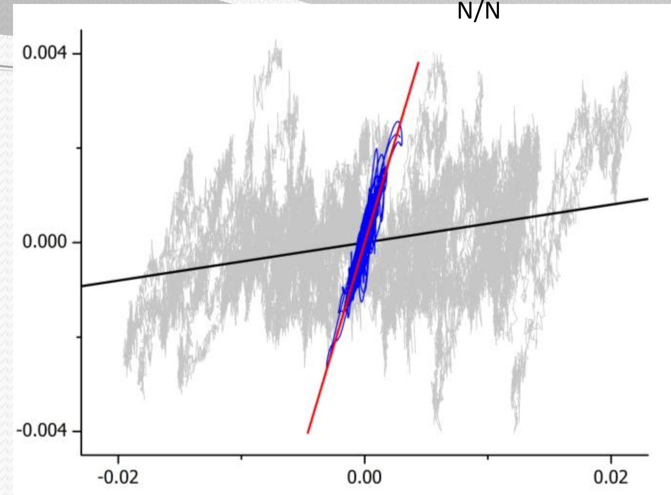
- Rocking mass: An mass will be set atop a smoothly curved base and will be rocked with a small initial rotational motion.



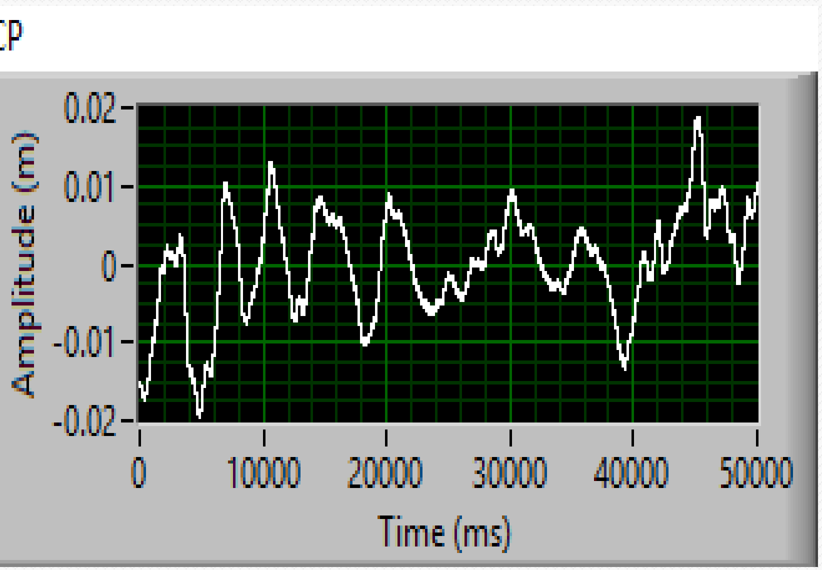
- Horizontal force applied to vertical pole: the mechanics of the set up ensures that the force of the ground on the pole intersects at the intersection of the force of gravity and the horizontal string, thus replicating the expected *F* variation of humans.

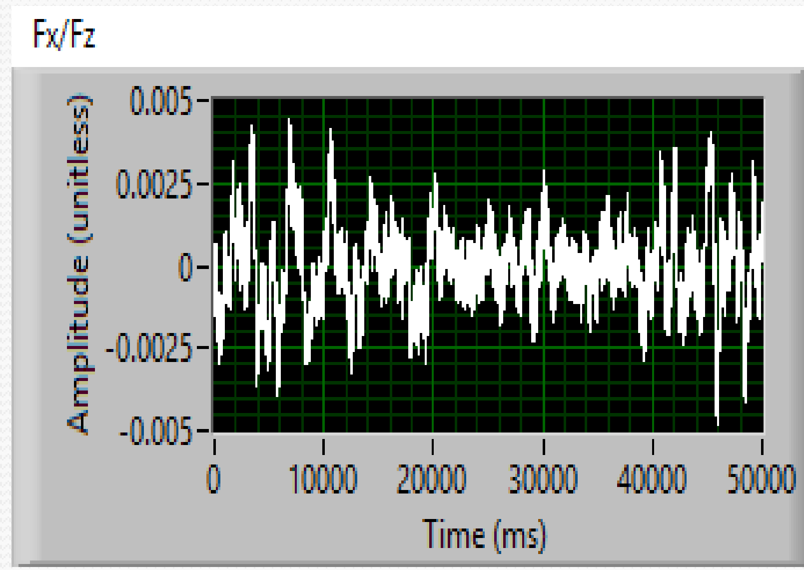
Pilot Data

Fx/Fz
N/N

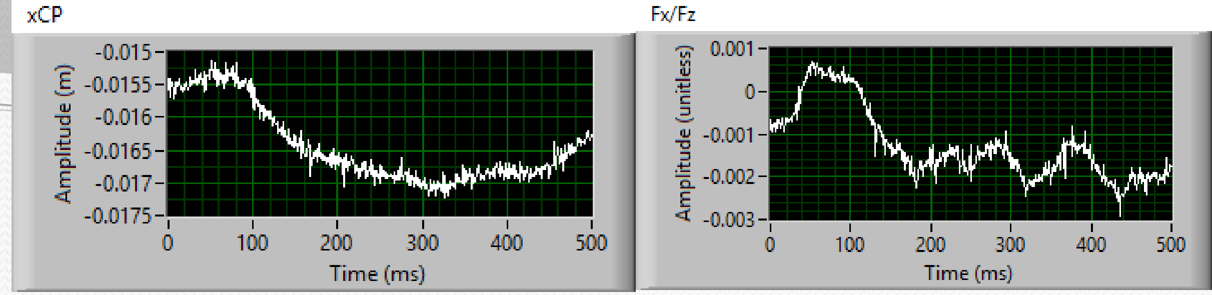


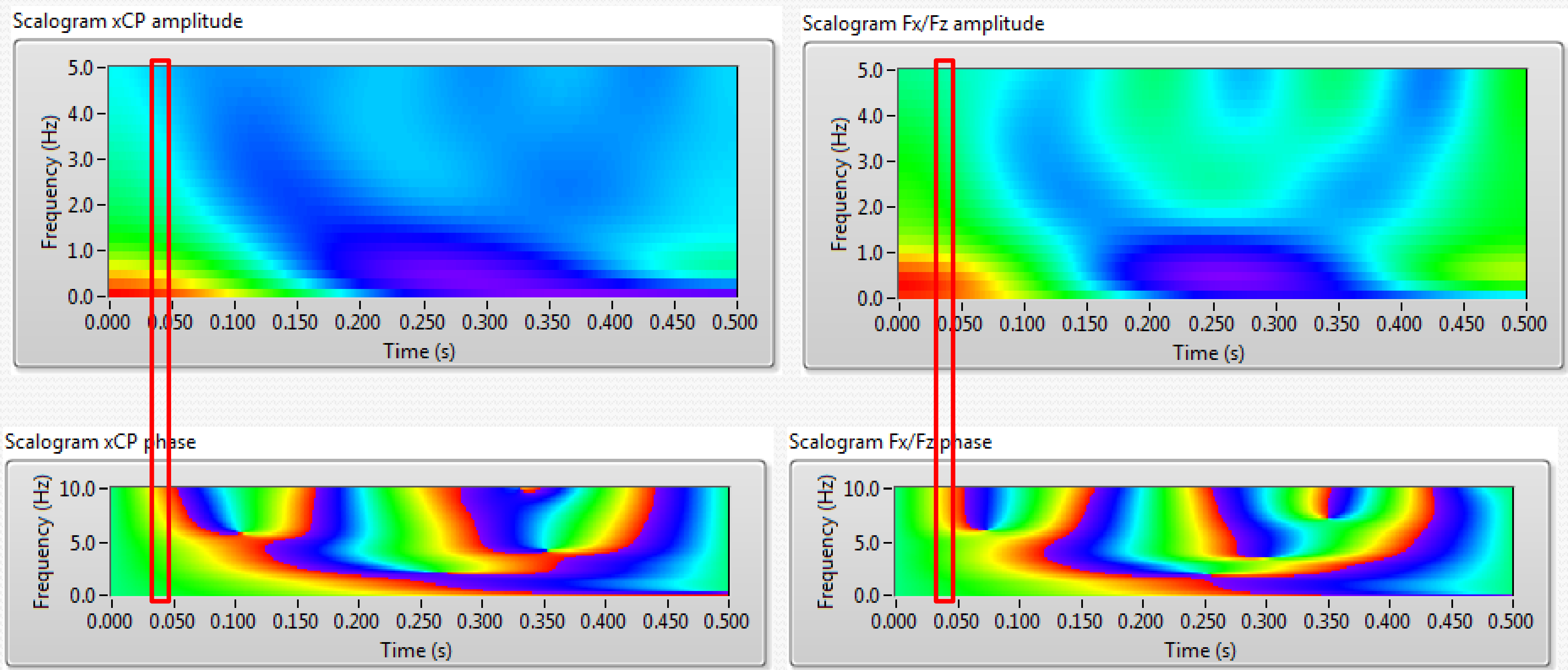
xCP (m)



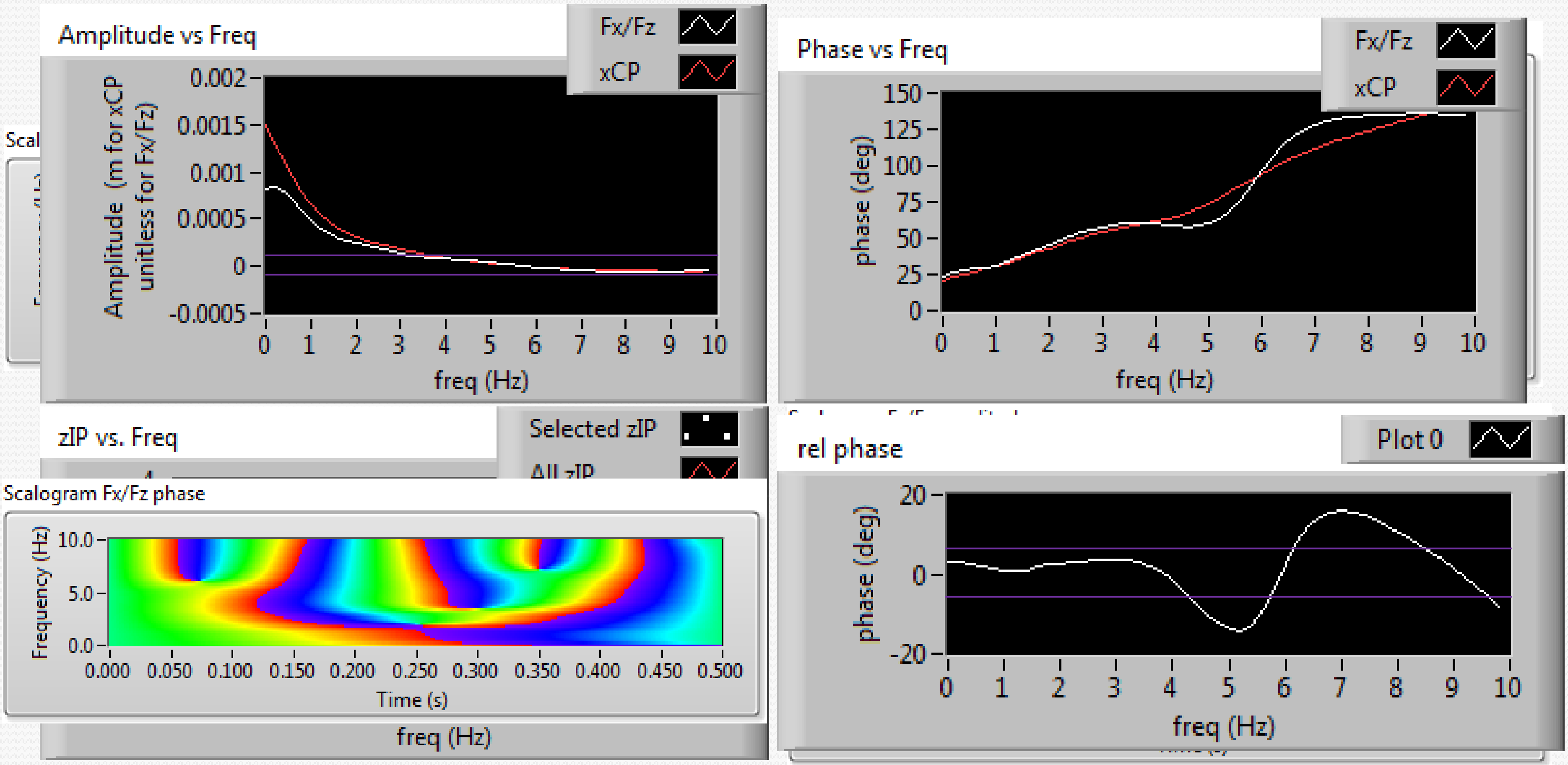


Pilot Data


xCP
Amplitude (m)
-0.015
-0.0155
-0.016
-0.0165
-0.017
-0.0175
0
100
200
300
400
500
Time (ms)
Fx/Fz
Amplitude (unitless)
0.001
0
-0.001
-0.002
-0.003
Time (ms)

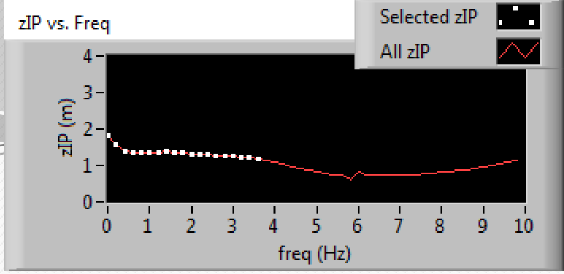

Scalogram xCP amplitude
Frequency (Hz)
5.0
4.0
3.0
2.0
1.0
0.0
0.000
0.050
0.100
0.150
0.200
0.250
0.300
0.350
0.400
0.450
0.500
Time (s)
Scalogram Fx/Fz amplitude
Scalogram xCP phase
10.0
5.0
0.0
Scalogram Fx/Fz phase

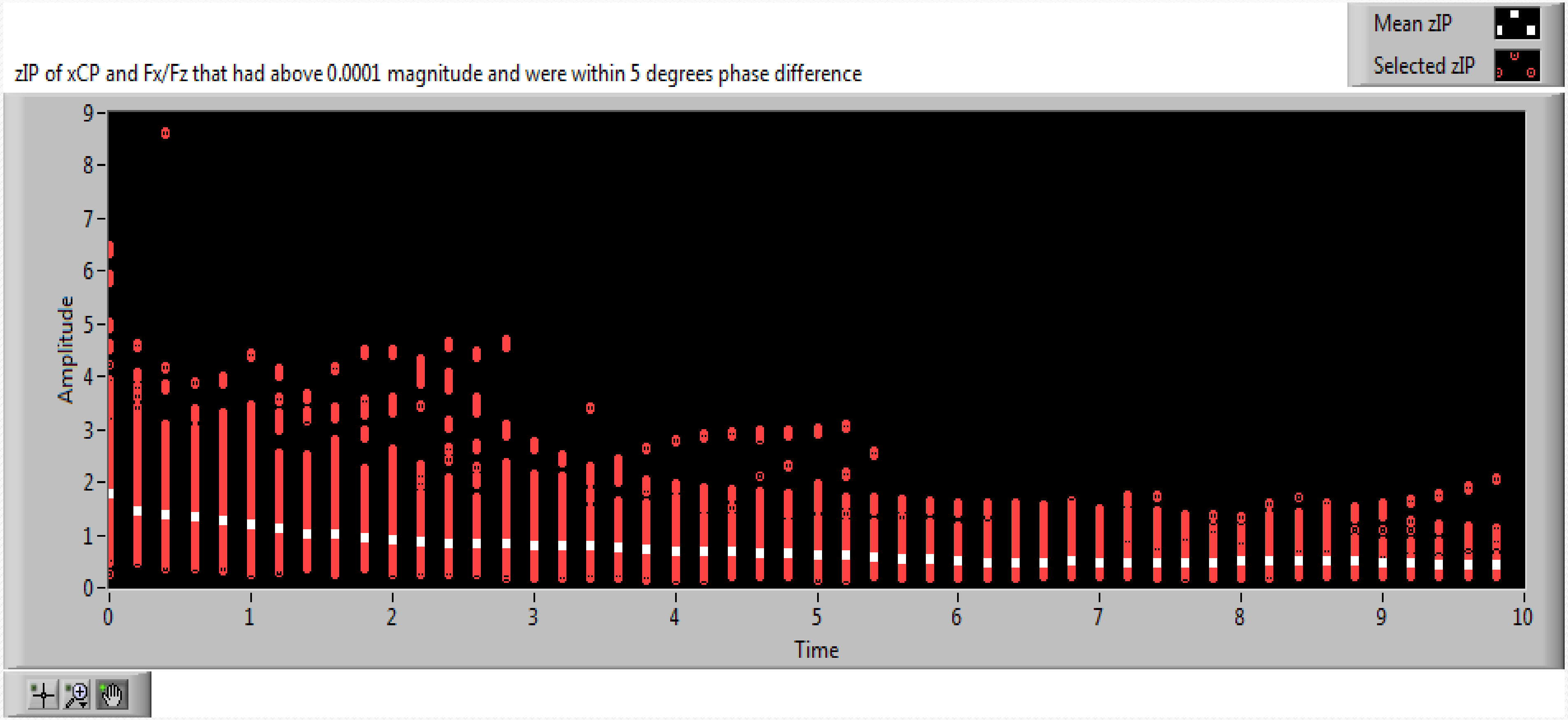
Pilot Data



Amplitude vs Freq
Fx/Fz
xCP
Amplitude (m for xCP unitless for Fx/Fz)
freq (Hz)
Phase vs Freq
Fx/Fz
xCP
phase (deg)
freq (Hz)
zIP vs. Freq
Selected zIP
Scalogram Fx/Fz phase
Frequency (Hz)
Time (s)
freq (Hz)
rel phase
Plot 0
phase (deg)
freq (Hz)

Pilot Data

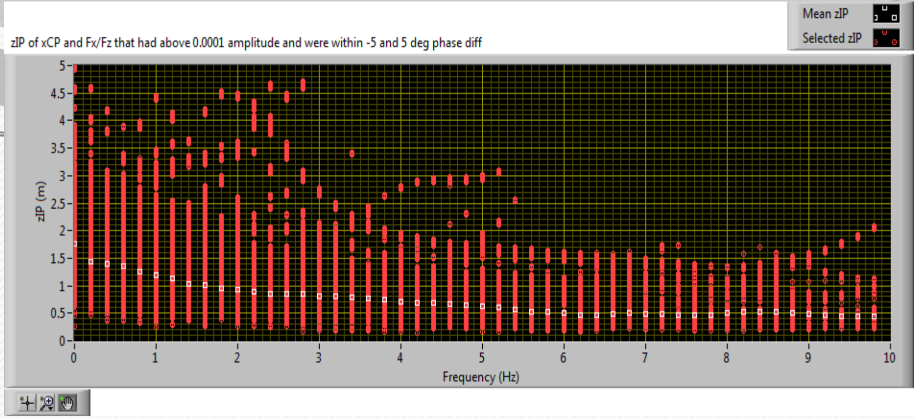

zIP vs. Freq
Selected zIP
All zIP
zIP (m)
freq (Hz)


Mean zIP
Selected zIP
zIP of xCP and Fx/Fz that had above 0.0001 magnitude and were within 5 degrees phase difference
Amplitude
Time

Review of Background

- Standing humans are capable of an infinite number of neuromuscular strategies to produce various patterns of xCP and F_x/F_z.
- In fact, there is no known constraint either from within or from outside the human neuro-musculo-skeletal system that would require humans to produce forces that directed at a point.
- The presence of an IP is an emergent property of specific joint torque coordination strategies applied to a multi-segmented mechanical body (e.g. constant hip and knee joint torques or constant joint angles).

Discussion



- Wavelet analysis of pilot data shows presence of IP behavior in one young healthy adult. It displays that zIP is higher for low frequencies and lower for higher frequencies.

- Though there is some variation with zIP across time, the mean zIP captures the general coordination of xCP and F_x/F_z to give frequency dependent zIP.

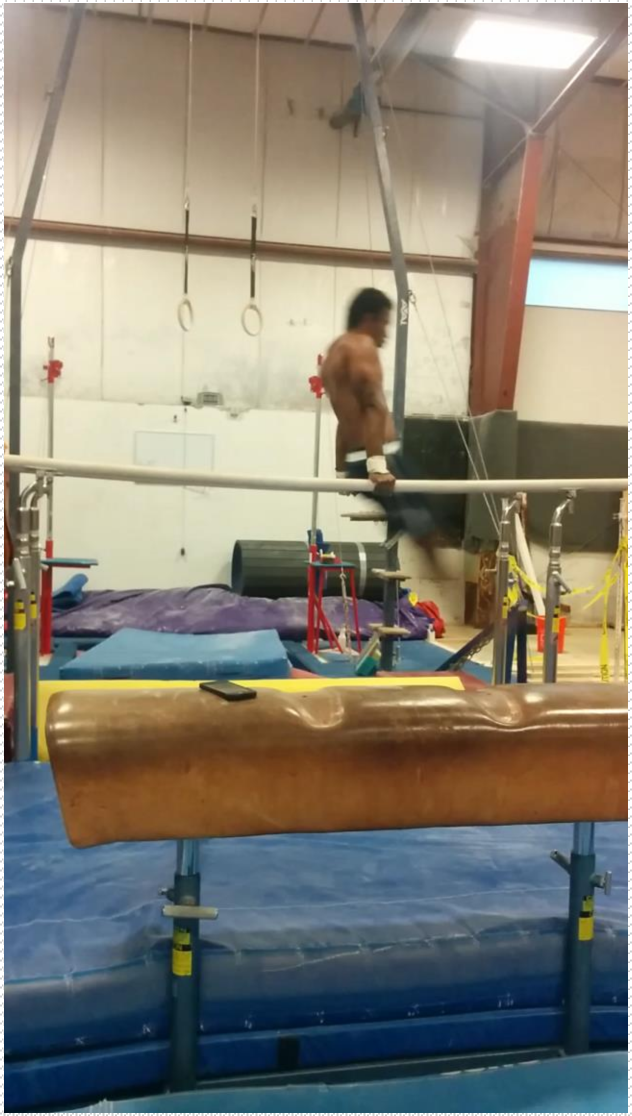
Conclusion

- This thesis will seek to discover
  - if there is a significant presence of IP among a sample of healthy adults
  - to further understand how the mechanical variable of the *F* is controlled to keep humans upright.

Thank You

- Dr. Kreg Gruben
- Thesis Committee
- Wendy Boehm
- Gruben lab undergrads
- Family
- Friends
- Kinesiology Department
- Virginia Horne Henry Foundation

My own failures in coordination



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