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Developing Motion Platform Dynamics for Studying Biomechanical Responses During Exercise for Human Spaceflight Applications

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Developing Motion Platform Dynamics for Studying Biomechanical Responses During Exercise

for Human Spaceflight Applications

by

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DEDICATION

I dedicate this thesis to my parents, Charles and Jahala, and to all who are passionate about human spaceflight.

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ABSTRACT

In future human spaceflight missions, with prolonged exposure to microgravity, resistive and aerobic exercises will be countermeasures for bone loss, muscle loss, and decreased aerobic capacity. Two of the exercises of interest are squats and rowing. The cyclic forces produced during these exercises are at relatively low frequencies which are likely to excite structural resonances of space vehicles. Vibration Isolation Systems (VIS) are being designed to be paired with future exploration exercise devices in order to prevent these cyclic exercise forces from impacting the space vehicle. The VIS may be configured such that a platform supports the human and exercise device. There is limited knowledge about the interaction between a human exercising and a dynamic platform. This research sought to fill part of the knowledge gap and study how the force inputs to the platform change as well as how exercise form was affected.

For this research, a system which can produce dynamic responses similar to those of a prospective VIS platform was used. This system is the Computer Assisted Rehabilitation Environment (CAREN) (Motekforce Link, Amsterdam, Netherlands). Simplified sinusoidal responses were implemented in a single degree of freedom, vertical (heave) motion, and also in multi-degree of freedom, heave and pitch motion. Human subject testing was conducted using four subjects with exercise experience. The subjects completed squats and rows, while standing, in both static (platform not moving) and dynamic (with platform moving) conditions. Subjects aimed to synchronize with platform motion, at the appropriate phase. Kinetic and kinematic data were collected via force plate measurements and motion capture, respectively. Testing was completed

with several predetermined frequencies for platform motion, but also at each subject's baseline frequency, which was the measured, comfortable exercise rate for the subject.

Data were processed and arranged in a presentable format. Results showed attenuation of the vertical component of forces between the comparable frequency static and dynamic platform conditions, as expected, for most subjects in the squat exercise. This was seen only in the heave with pitch condition during rows for most subjects. Results also showed increasing amplitude of forces as frequency increased, which was also expected. Knee angle range of motion was well maintained between static and dynamic conditions. These results suggest that conditions desirable for both VIS and exercise are possible. Further testing and extended analysis at additional amplitudes, frequencies, and degrees of freedom are of interest and warrant further study.

This work contributed knowledge and data regarding the forces involved and human kinematics produced while exercising with platform motion. These data can further be used as inputs and requirements for VIS design work, VIS and human biomechanical modeling, and exercise countermeasure development. This work achieved the objectives of establishing an appropriate test environment and developing platform dynamics in which human-VIS interaction could be studied. It also acted as a proof-of-concept for future testing which can be conducted to answer new questions relating to dynamic platform motion effects on human activity.

CHAPTER 1: INTRODUCTION

1.1 Motivation

1.1.1 The Big Picture

As humanity continues to venture out into the solar system and the duration of space missions become longer, crew members will face prolonged exposure to reduced gravitational environments so long as artificial gravity is out of reach. When the human musculoskeletal system is unloaded, it begins to deteriorate [1]. This poses an obstacle for transitioning between gravitational environments such as microgravity to Martian gravity, which is about 38% of Earth's gravity [2]. Not having the strength to walk or lift one's weight after landing on a planetary body is a threat, especially given an emergency egress or other emergency situation. Hence, countermeasures are implemented throughout microgravity travel to mitigate some of these health risks. Exercise countermeasure systems (CMS) are needed to prevent significant bone loss, muscle loss, and decreased aerobic capacity. Nutritional and pharmaceutical countermeasures have also been used during historical space missions as well as on the International Space Station (ISS) and are sometimes paired with exercise [3]. A more holistic approach to the problem of bone and muscle loss, among other health issues, has precedence. However, for considerations in this work, only the exercise countermeasure is considered and solely from a loads perspective rather than a microbiological one.

1.1.2 The System

In future long-duration missions, exercise CMS (also referred to as Exploration Exercise Devices (EEDs)) are driven to be more compact, requiring less stowage and operational volume

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than current systems on the ISS, yet must still be able to provide the same benefits of use. The exercise CMS must also be able to be integrated in the space vehicle and not cause interference with other systems or the structure itself. An integrative approach is needed to study this human-CMS-vehicle system so that the interactions between components are considered. Further insight into these areas is provided in 2.1 Exercise and Countermeasure Systems for Spaceflight.

1.1.3 The Focus

There is an addition to the system in between the exercise CMS and the vehicle – a Vibration Isolation System (VIS). Further insight is provided in 2.2 Vibration Isolation in Microgravity. A VIS, in this context, is intended to limit transmission of harmful vibrations, generated by the human during exercise, to the vehicle, but it also has the potential to affect the interaction between the human and CMS. The motivation behind the focus of this research is to fill part of the knowledge gap in the VIS-human interaction (how each will affect the other). Though there is some microgravity research on human biomechanics[1] and motion capture that was conducted in early space missions [4,5], it was not until recently that full musculoskeletal biomechanics during exercise have been investigated in microgravity on the ISS [6,7]. The results of these studies should provide information which will help in the assessment of the benefits and limitations of ISS CMS and exercise regimes. The results may also provide more information about VIS performance and the effects on the user in microgravity. However, these data will relate to current CMS and not necessarily to future systems, where the VIS designs may be significantly different. Since future VIS designs are just that, design concepts, and have not undergone human testing, the knowledge gap of VIS-human interaction remains. Current analyses consider only vibrational inputs measured from static ground conditions and knowledge regarding how these

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[1] Human biomechanics is a study of movement and forces on the body, among other physiological measures

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inputs differ in dynamic ground conditions (a moving VIS) is limited. This work seeks to reduce the knowledge gap so that human biomechanics information can be considered and incorporated into designs to obtain the most effective systems.

The work is also driven by the need for experimental data which can be used to enhance and verify computational models of the human-CMS-vehicle system. Experimental data produced from this research will be provided to the Digital Astronaut Simulation group at the National Aeronautics and Space Administration (NASA) Johnson Space Center through research collaboration as part of a NASA Space Technology Research Fellowship.

1.1.4 Roadmap Gaps

In addition to addressing the knowledge gap areas provided in 1.1.3, this research also aligns with the 2015 NASA Technology Roadmap documents (which outline capabilities and milestone dates for future exploration missions). One area is Long-Duration Health (Technology Area 6.3.2) which highlights the need for novel exercise countermeasure "hardware and protocols" along with "integrated biomechanics" and also for "new generation VIS technologies" [8]. This research is also synergistic with Modeling (Technology Area 11.2) as it provides information for Human-System Performance Modeling, Software Modeling, Model Checking, and Analysis Tools for Mission Design. This work aligned within the development start of these roadmap areas. Hence, it contributed to the field at an opportunistic time.

1.1.5 Problem Statement

Currently, human biomechanics information is lacking for interaction with vibration isolation systems on exercise devices designed for space exploration applications. This research addresses the problem through the creation of a comparable test environment where the interaction

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between the human, while exercising, and a dynamic platform can be studied, and kinematic (motion) and kinetic (force) information can be provided.

1.2 Objectives

The high-level aims of this work are enumerated below:

1. To implement a dynamic response in up to two degrees of freedom (DOF) on a motion platform which is comparable to prospective VIS motion.

2. To study the effect of platform motion on human kinematic and kinetic response while completing resistive and aerobic exercise.

The specific aims, which were stages needed to achieve the objectives, are shared in Table 1. Additional details associated with these aims will be shared throughout subsequent chapters.

Table 1: Specific Aims of the Research

Aim 1	Program a laboratory motion platform to have responses in degrees of freedom which could be activated independently or together.
Aim 2	Create a test protocol for human subject testing of squats and rowing exercises on a dynamic platform.
Aim 3	Quantify the differences in external forces between exercise during static platform and dynamic platform conditions.
Aim 4	Quantify differences in joint angles representative of exercise form between static platform and dynamic platform conditions.

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CHAPTER 2: BACKGROUND

2.1 Exercise and Countermeasure Systems for Spaceflight

2.1.1 Exercise in Microgravity

Resistive and aerobic exercises are completed onboard the ISS for approximately 2.5 hours daily [9]. Resistive exercise includes squats, deadlifts, and heel raises. Aerobic exercise includes running and cycling. In all cases, the user of the exercise device receives loading by being constrained between lever arms, wearing a harness with bungee cords, and other similar constraints. More information regarding the configurations is shared in 2.1.2 Countermeasure Systems on the ISS. Different exercise regimes have been tested such as SPRINT, where two separate exercise sessions were required daily for three days per week with short, medium, and long aerobic intervals to be performed weekly [10]. These regimes may make short-term exercise more effective, although research is still ongoing. Rowing has been used as a countermeasure historically, such as with the MK Rowing Machine used in Space Shuttle missions. Research showed that the rower maintained aerobic capacity within 6-12% of preflight measurements for those missions [11]. Recently, rowing is being re-considered as a prospective aerobic exercise. This influenced a decision to incorporate rowing as an exercise to test in this research. In preliminary results from studying kinematics of rowing while using a prospective future exploration exercise device in a parabolic flight, differences were observed in exercise form [12,13]. Without a seat for a constraint as there would be on a rowing ergometer, paired with the orientation of the foot holds on the device, users had a tendency to extend the back, almost out

straight with lower limbs. A seat may be included in future configurations, but is not currently included. Squat exercises with CMS can be front squats or back squats with varying stances.

2.1.2 Countermeasure Systems on the ISS

There are three primary CMS (exercise devices) used on the ISS: the Cycle Ergometer with Vibration Isolation and Stabilization (CEVIS) system, Treadmill with Vibration Isolation and Stabilization System (TVIS), and the Advanced Resistive Exercise Device (ARED) [14-16]. On CEVIS, shown in Figure 1, the user can choose various handle configurations which differ from bicycle configurations. Shoes worn by the users are secured on the cycle pedals.

Figure 1: CEVIS (Credit: NASA ISS032-E-027050, Public Domain)

On Treadmill 2 (T2), part of TVIS as shown in Figure 2, adjustable bungees on each side of the body connect between a shoulder and waist harness and the side of the treadmill to provide loads ranging from 40 to 220 lbs. [15].

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Figure 2: Treadmill 2 (T2) (Credit: NASA ISS036-E-005384, Public Domain)

ARED, shown in Figure 3, is modular and can be set for all resistive exercises listed in 2.1.1. It can provide loads ranging from 10 to 600 lbs. on bar and 5 to 150 lbs. on cable [16]. The ARED facility on-orbit mass is required not to exceed 700 lbs. The system can simulate the inertial load of free weights.

Figure 3: ARED (Credit: NASA ISS039E011261, Public Domain)

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2.1.3 Future Countermeasure Systems

Future CMS, or Exploration Exercise Devices (EEDs), have been proposed for use in future missions. A general commonality between the devices is the use of cables to provide the loads to the human. One such EED, the Advanced Twin Lifting and Aerobic System (ATLAS), builds on design work from another precursory device, Resistive Overload Combined with Kinetic Yo-yo (ROCKY) [17]. ATLAS uses two cables and can provide 10 to 60 lbs. of resistance in lifting mode and speeds up to 120 in/sec for cable stroke in aerobic rowing exercise. It can apply both static and inertial loads. At approximately 1/5th the volume and mass of ARED, and low power requirements, the device is considered to meet the needs of future exploration missions [17]. The Miniature Exercise Device (MED-2), another EED, is a single cable system which has been tested on board the ISS. It has the ability to provide both constant loads, progressive loads, and non-linear loads via precise control from a robotic type actuator. The MED generations of hardware are working toward a device that is an order of magnitude lighter and smaller than existing CMS on the ISS [18].

2.2 Vibration Isolation in Microgravity

2.2.1 Vibratory Environment

The ISS, being a low-earth orbit laboratory, is in constant free fall around the Earth, providing a nearly 0-G environment. The typical accelerations/decelerations the ISS experiences are due to drag from the thin atmosphere, thrusters, docking, onboard equipment, and crew activity. The structural modes of the ISS are low frequency vibrations from about 0.1 Hz to 5 Hz [19]. Considering that much of human activity can occur within this frequency range, this can be of concern. For example, exercise that helps to prevent muscle and bone loss while in microgravity is typically <3 Hz. In an ARED man-in-the-loop test (MILT), it was found that the frequency

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range, in one of three excited DOFs, of squat, deadlift, and heel raise was from 0.09 Hz – 1.18 Hz [20]. Niebuhr and Hagen provide that, for between 0.18 Hz and 0.28 Hz (given an ISS structural mode around 0.24 Hz), the allowable cyclic load is limited to 1.7 N (0.4 lbf). They note that ARED exercise at 0.24 Hz produced loads "as high as 67 N (15 lbf)". Exercise in general, using any device, at 0.24 Hz would be expected to produce loads greater than 1.7 N. Therefore, it is important that there be attenuation of the low frequency vibrations generated by human motion to minimize transfer to the station.

2.2.2 Vibration Isolation Systems on the ISS

Each of the countermeasure systems in 2.1.2 include a VIS which work to attenuate forcing frequency vibrations by lowering the natural frequency of the exercise-VIS system. Each is passive and designed for the specific device.

2.2.3 Future Vibration Isolation Systems

The VIS for future EEDs could be passive (e.g., mass spring damper systems), or active (e.g., controllable actuators). A passive VIS has the advantages of not requiring power and disadvantages of being limited in modularity. An active VIS has the advantages of being more modular and having closed-loop isolation capabilities and disadvantages of requiring power and having a more difficult transmissibility problem. The use of an active VIS might still require a passive VIS component. There is also an interest in having VIS capable of supporting multiple EEDs. The system would most likely consist of a VIS separating a platform, with human and EED, from the space vehicle, as illustrated in Figure 4.

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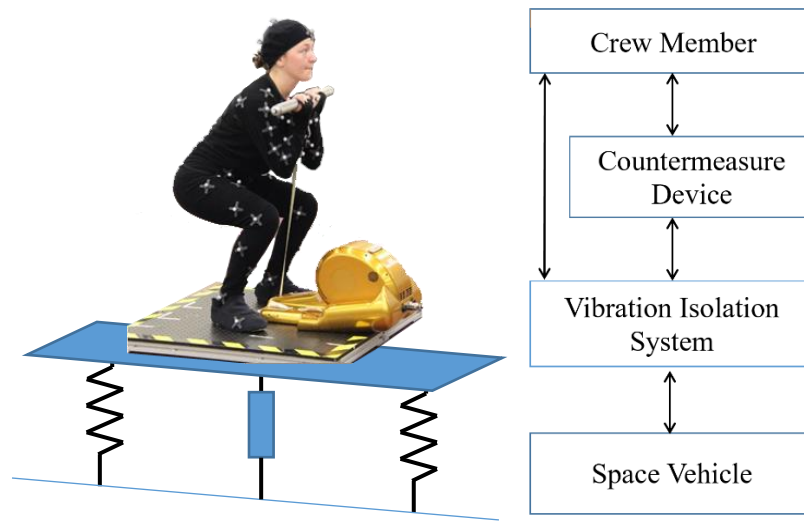
Figure 4: Depiction of Interactions Between System Components

2.3 Biomechanics of Exercise

Squat and row exercise studies typically incorporate the external loading used in those exercises such as free weights/dumbbells for front squats, back squats, or goblet squats and ergometer resistance/oars for rowing. It was of interest for this research, however, to study exercise in the absence of external loading, as described later in 4.4 Environment Distinctions.

A study by Dali et al. (2013) provides comparable conditions for squats without external loading [21]. In this referenced study, approximately half of the body weight and forces were measured from a single force plate underneath one foot. Squats were completed at approximately 1 Hz. Under these conditions, the maximum ground reaction forces were 383.22 +/- 52.63 N. Given this was reported as 64.57% of the mean body weight (60.42 +/- 6.37 kg) supported, the total ground reaction force was likely 1.55 times that amount, or approximately 594N.

The knee angle range of motion expected for squats is usually based upon exercise prescription. These may be partial squats (40° knee angle), half squats (70 to 100°), and deep squats (greater than 100°) [22].

The row exercise used in this study is unconventional in that it is performed while standing and without external force. Still, there is an interest to target the form and forces experienced in conventional rowing. Buckeridge (2013) reported that peak foot forces had a linear relationship with maximum handle force [23]. Maximum handle forces were reported as 921.9 +/- 86.7 N for the Elite group of rowers. Considering foot force measurements only, graphs provided peak foot forces (normalized to the rower's body mass) at roughly 13 N/kg at various stroke rates for female scullers and sweep rowers and roughly 14 N/kg for male rowers.

Also reported was knee angle during rows while the foot stretcher was at various positions. Considering the provided data for knee angle at Catch and Finish stages of rowing in [23], the average knee angle range of motion was approximately 124º.

CHAPTER 3: THEORY

3.1 VIS/Platform Motion

As described in 2.2.3 Future Vibration Isolation Systems, it is likely that a future VIS will include a platform in which EEDs can be mounted. In this way, the platform is representative of VIS motion. For all intents and purposes in this thesis, the terms "VIS" and "platform" are interchangeable. This is important in connecting the Experimental Design Hardware used in this research to VIS.

3.1.1 Isolation and Transmissibility

The problem, in this case, is the isolation of the source of vibration (exercising crew member) from the surrounding environment. The isolation problem is then analyzed in terms of reducing the force transmitted by the source into the system [24]. Isolators are designed with use of the transmissibility ratio, which is the ratio of the transmitted force (F_T) to the input force (F_0). In the case where the driving force is harmonic, the transmissibility ratio (TR) is given by Eqn. 1 below. A TR < 1 is the target for isolation.

$$TR = \frac{F_T}{F_0} = \sqrt{\frac{1+\left(2\zeta\frac{\omega}{\omega_n}\right)^2}{\left(1-\frac{\omega}{\omega_n}^2\right)^2+\left(2\zeta\frac{\omega}{\omega_n}\right)^2}} \qquad \text{(Eqn. 1)}$$

In the transmissibility equation, ζ is the damping ratio of the isolator, ω is the forcing frequency and ω_n is the natural frequency. When ω/ω_n is greater than $\sqrt{2}$, isolation occurs. This research considers exercise at various frequencies. The forces associated are considered to be harmonic functions.

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3.1.2 Ideal Cases

If feasible, it would be desirable for vibration suppression to have an absorber type system, but in a less conventional way since the motion of the primary mass (the human), which provides the disturbance, should actually be maintained. A platform with a relatively large mass (i.e., larger inertia) may absorb the input forces. However, minimizing hardware mass is an important requirement in spaceflight.

In the case where the platform is massless, isolation of forces requires displacement of the platform equal and opposite to the displacement of the human center of mass. It was of interest to study this worst-case scenario in the experimental design of this research, but limitations were imposed by experimental hardware as well as the experimental design itself, described in Chapters 5 and 7. The platform of a future VIS will have mass, in which case, the center of mass of the system is considered. The magnitude of displacement needed for attenuation of forces is then reduced.

These displacements may be required in multiple degrees of freedom as forces and moments associated with exercises can occur in multiple degrees of freedom. The rate of these displacements specifying the platform motion (i.e., the platform response) may be time varying harmonic functions.

3.1.3 A Simplified Response

At steady-state, certain exercises, such as squats, can be primarily represented by a sinusoidal response because of the cyclic nature of the motion. This can apply to certain trajectories of parts on the body as well as to ground reaction forces. The sinusoidal response for displacement as a function of time is shown in Eqn. 2, and for orientation in Eqn. 3, respectively.

$$y(t) = A * \sin(\omega t + \varphi) \tag{Eqn. 2}$$

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where A is the amplitude (in unit length), ω is the angular frequency (in rad/s), and φ is the phase (in rad).

$$\theta(t) = A * \sin(\omega t + \varphi) \qquad \text{(Eqn. 3)}$$

where A is the amplitude (in degrees), ω is the angular frequency (in rad/s), and φ is the phase (in rad). Note that phase is not needed in this application for either Eqn. 2 or Eqn. 3, where at time equals zero, displacement and orientation equal zero.

The velocity and acceleration equations for the sinusoidal response, needed to find platform displacement limitations in 5.1.2 Motion Platform, are provided by Eqn. 4 and Eqn. 5, respectively. Note that the equations also apply to angular velocity ($\dot{\theta}(t)$) and angular acceleration ($\ddot{\theta}(t)$).

$$v(t) = \omega A * \cos(\omega t + \varphi) \qquad \text{(Eqn. 4)}$$

$$a(t) = -\omega^2 A * \sin(\omega t + \varphi) \qquad \text{(Eqn. 5)}$$

For this work, it was decided to implement a sinusoidal response over the ideal case for the reasons enumerated below:

1. Simplification of the problem:

    i.   Since the development of future CMS and an accompanying VIS was current ongoing research in space exploration, it was most practical at the time to implement a motion not tied to any specific design parameters. It was in the best interest of contributing to the research to not make assumptions for VIS motion which may not be representative of a final design. Instead, the simplified motion can potentially contribute to many designs rather than be restricted to one (i.e., more transferrable information).

    ii. Engineering analyses often begin with a simplified version of a more complex problem.

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2. Consistency throughout testing:

    i. Using a pre-determined response enables all study participants to test with the same conditions (general motion). In this way, it is more feasible to compare results and draw conclusions. Parameters that should be individualized, like amplitude of the motion, are adjustable through the sinusoidal response.

3. Safety concerns/development time:

    i. The ideal case requires closed-loop control of the platform motion, where force or kinematic information from the user is the feedback. With human-in-the-loop control, there is a greater potential for the system to become unstable, posing a concern for the safety of the user. Safety protocols can be implemented in the control in the form of filters, safeguards (limits), and fault triggering, but in weighing development time versus benefit, it was considered that this should be left to future work. It is important to note that implementing the simplified "open-loop" response should be a precursor nevertheless for testing and verification purposes.

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CHAPTER 4: EXPERIMENTAL DESIGN

4.1 Overview

In order to meet the objectives of this research, an appropriate test environment was created. This entailed using resources available in the Center for Assistive, Rehabilitation, and Robotics Technologies (CARRT) at the University of South Florida (USF). A dynamic motion platform, described in Chapter 5, Experimental Design Hardware, was one of those resources, and is considered an analog to a human exercise VIS in this work. Chapter 6, Experimental Design Software, expands on the control of this system and how the VIS responses were programmed.

Human volunteers were recruited to be subjects of the research, detailed in Chapter 7, Experimental Design Implementation. To further meet the objectives of this research, kinetic and kinematic data were collected in the form of motion capture and force plate measurements while the subjects engaged in squat and rowing exercises.

The experiment tested the squat and row exercise under various conditions. Throughout the subsequent chapters, "Static" refers to when the motion platform is not moving. "Dynamic" refers to when the motion platform is moving according to the simplified responses (from 3.1.3 A Simplified Response). Various frequencies of the response were tested, as explained in 4.3 Frequency Selection. There were also test amplitudes and frequencies selected that were individualized to each subject.

Platform motion was pre-programmed. None of the real-time force or motion capture measurements were used to drive platform motion in this thesis work, though this is of interest in future work.

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4.2 Constrained DOFs

The ARED MILT [20] was a primary reference for selecting appropriate test constraints for this thesis research. The study provided information relevant for VIS related modeling and design work extendable beyond ARED to future CMS. It highlighted that one of the worst-case exercises in terms of vibrational amplification, squats, excited the vertical DOF (along Y-axis in a right-handed coordinate system) and the rotation about X-axis. This pointed out potential DOF of interest for this research. It was confirmed with NASA's Digital Astronaut Simulation group that these two degrees of freedom, vertical translation and pitch, were of interest for ongoing work.

Platform motion was constrained to 1 DOF (translation) and 2 DOF (translation and rotation) motion for this research. Table 2 shows the DOF implementation, where "heave" is vertical translation. It was considered during design of the experiment that the rowing exercise was more important to test under the 2 DOF condition as it would excite the rotational DOF more than squats. Hence, only rowing includes the additional tests.

Table 2: Degrees of Freedom for Platform Motion Tested for Each Exercise

Exercise	DOF Implemented
Squat	Heave
Row	Heave Heave + Pitch

Pitch angles tested, which were input amplitudes to the sinusoidal response for orientation, are presented in Table 3. These were determined based on consideration of what may be valuable to NASA's Digital Astronaut Simulation team, since analysis may include this range of angles, and consideration of operational volume of a VIS. During design of experiment testing, a user was

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able to complete motions while remaining stable and so this range of angles was confirmed to be appropriate. Angles greater than 3 degrees were tested but were considered extra tests, as detailed in 7.3.4 Experimental Trials.

Table 3: Pitch Amplitudes Selected for Study

Pitch	0.5º	1º	2º	3º

4.3 Frequency Selection

The ARED MILT [20] was also referenced for selecting frequencies of interest at which to test. This is because it provided frequencies at which the human subjects performed squat exercises during ARED use. Frequencies of interest were also considered from NASA's Acceleration Environment guide [19]. The frequencies selected for experimental testing, and the reasons why, are provided in Table 4.

Table 4: Platform Frequencies Selected for Study

Frequency Selected	**Reason**
0.10 Hz	The minimum value for Squat frequency in the ARED MILT was 0.09 Hz (so it is close), and 0.10 Hz is a structural mode of the ISS
0.35 Hz	The average value for Squat frequency in the ARED MILT was 0.34 Hz (so it is close), and this is the midway point between the other two frequencies
0.60 Hz	The maximum value for Squat frequency in the ARED MILT was 0.60 Hz, and higher frequencies are of interest to rowing. (This converts to 36 strokes per minute, a fast pace)

In addition to these fixed frequencies at which all subjects tested, subject specific "baseline" frequencies were tested. The process for obtaining the baseline frequencies is shared in 7.3.2 Pre-Test Measurements. These baseline frequencies were used to drive the platform sinusoidal motion

at near each subject's most comfortable exercise rate for one of the Experimental Trials. This was to allow more direct comparison between Static platform and Dynamic platform conditions as it was considered that a self-paced frequency would be more controllable. To expand, it is easier to set the Dynamic platform trial to a subject's self-paced, comfortable frequency than it is to obtain a Static platform trial where the subject is instructed to exercise at a specific frequency. In this way, the baseline frequency trials at least were directly comparable in order to better understand the effect of platform motion. The other frequency trials provided insight to different Dynamic conditions, but cannot necessarily be compared directly against the Static baseline. Frequency variation of exercise can affect form just as a moving platform can, so these test cases must be isolated for comparisons.

4.4 Environment Distinctions

This section highlights some conditions in the test environment which may be different than those experienced in other 1G (Earth gravity) testing facilities as well as from the microgravity case. It also provides some insight into why these differences were deemed acceptable for the experimental design.

Human subjects did not use external weights (e.g., free weights or an exercise device) during the study. From the perspective of a platform style VIS (where both a device and the human are secure on top of a platform), load due to an exercise device is combined with forces from the human. For this reason, adding resistance was not essential to this study. Adding load to the human may change exercise form and increase ground reaction forces, but it was of most interest to study the effect of dynamic platform motion on exercise form and ground reaction forces rather than external resistance. This allowed greater transfer of knowledge to various countermeasure systems designed for these exercises as well.

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In the 1G condition, there is a tendency for a person to align with the gravity vector in order to maintain balance. In this experiment, the DOF of most interest (heave) aligns with the gravity vector as well as the line of action for the exercise motions. Since one would want to maintain exercise along that line in the microgravity condition, it was considered that exercise motion could be most comparable between gravitational conditions in this configuration. Though considered, no fixed angle tilt was implemented for this reason. Also, by keeping the environment in the described configuration, this work provides a reference for a ground (1G) unit for the system which might precede the flight hardware. During platform pitch, there was greater concern for balance becoming a factor. However, factors relating to stability are still of interest. Further explanation of 1G test applicability is provided in 10.2 Limitations and Future Improvements.

4.5 Conditions and Measures

Conditions to be tested were determined based on the essential comparisons which needed to be made. Table 5 provides these comparisons. These comparisons were chosen as they relate both to exercise and VIS kinematics and kinetics. Conditions tested to provide data for these comparisons are listed in 7.3.4 Experimental Trials.

Table 5: Comparisons Used in Study

Comparisons
Static versus Dynamic (at baseline frequencies)
Frequency Variation
1 DOF versus 2 DOF

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Table 6 describes the measures studied from the experimental data collection in order to fulfill the objectives of this research. The subsequent chapters explain how these parameters were measured and analyzed. Results are presented in Chapter 9.

Table 6: Outcome Measures

Kinetic Outcome Measures	Description	Purpose	Contribution
Ground Reaction Force Profiles	Force measurement between ground and each foot	To observe how the force changes during the exercise cycles in Static and Dynamic conditions	External loads on human; Input to VIS
Average Maximum Force	The average of the peak forces across exercise cycles	To determine the maximum force at the human-platform interface	Max. loads on human/ exercise effectiveness; VIS effectiveness
Average Force Range	The average of the range of forces across exercise cycles	To determine the amplitude of cyclic forces	Cyclic loading on human; vibration input
Force Frequency Matching	Alignment of force peaks and troughs with platform cycle	To observe the human ability to match to platform motion	Adaptation of human to VIS
Kinematic Outcome Measures	Description	Purpose	Contribution
Knee Angle Trajectories	Knee angle over time	To observe difference in exercise form	Exercise completion
Knee Angle Range of Motion (ROM)	Average range of knee angles across exercise cycles	To compare difference in exercise form between conditions	Exercise completion
Other Measures	Description	Purpose	Contribution
Participant Feedback	Questionnaire with Likert scale and open-ended questions	To gain valuable insight into participant perspectives	Explanation of results; Design of CMS and VIS

Each of these measures were pursued because they relate either to exercise performance and assessment of the ability to complete exercise or to VIS design constraints, or both.

CHAPTER 5: EXPERIMENTAL DESIGN HARDWARE

5.1 CAREN

5.1.1 System Overview

The Computer Assisted Rehabilitation ENvironment (CAREN) (Motekforce Link, Amsterdam, Netherlands), shown in Figure 5, is an immersive environment which includes a 6 DOF motion platform, motion capture system, two force plates, split-belt treadmill, and a 180-degree (panoramic) projection screen with seamless display from three projectors. All components were needed for the research with the exception of the treadmill as only stand-in-place exercises were within the scope of the work.
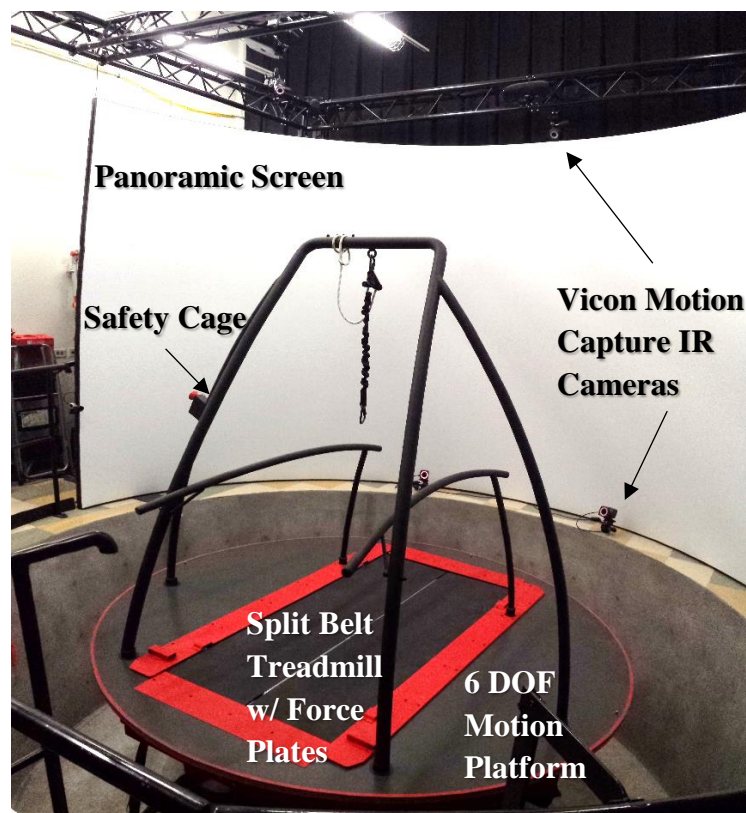
Figure 5: CAREN System

The 6-DOF motion platform provided the key capability for this research. By having control of the dynamic platform in 3 translational and 3 rotational DOFs, the platform can produce motion comparable to that of a VIS, whether active or passive. Since the CAREN is human rated, it is an invaluable resource for conducting research in the problem area, especially while design of future countermeasure and vibration isolation systems is ongoing.

The laboratory also includes equipment and resources such as a weigh beam physician scale with height rod, flexible tape measures, video cameras, and safety harnesses. These items were used in the experimental collection.

The system also includes a number of built-in safety features such as handrails on the platform, a safety tether for attaching the harness, sensors which trigger the platform to stop and return to a settled position if a person is too close to the edge, and emergency stops on the platform and next to the operator which cut power to the system. There are also safety features which can be implemented in the software, such as safety filters on the platform motion which limit permissible accelerations/decelerations, especially while changing direction of motion, so as not to allow unintended instability for the safety of the user and damage to the system.

5.1.2 Motion Platform

The CAREN motion base at the University of South Florida is a Moog (East Aurora, NY, USA) MB-E-6DOF/12/1000KG. It has a gross moving load of up to 1158 kg [25]. The base is of a Stewart Platform configuration which includes 6 electric linear actuators attached in three pairs to the bottom of a platform, providing 6-DOF motion, as outlined in Figure 6. The 3 translational DOF are left/right (X/Sway), upward/downward (Y/Heave), and forward/backward (Z/Surge). The 3 rotational DOF are tilt forward/backward (about X/Pitch), rotate about center (about Y/Yaw), and tilt side to side (about Z/Roll).

23
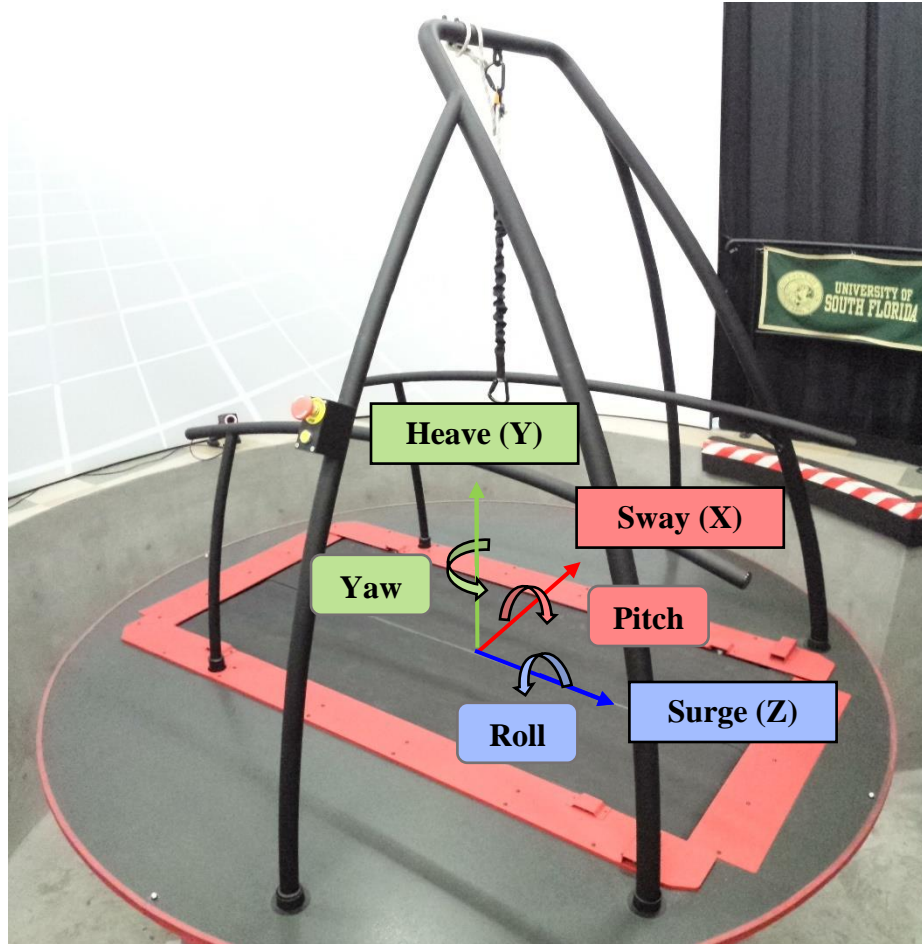
Figure 6: CAREN Motion Platform with DOFs Specified

In each single DOF of interest, heave and pitch, the maximum excursion (due to imposed software limits) is shown in Table 7, which differs from those provided in the MOOG specifications.

Table 7: Excursion Limits of CAREN Platform

DOF	Max. Excursion
Heave (only)	+/- 0.18 m
Pitch (only)	+/- 18º

The Moog specifications provide the constraints for velocity and acceleration shown in Table 8. Figure 7 shows the limiting curves of allowable amplitude and angular frequency inputs to Eqn. 2, Eqn. 4, and Eqn. 5 at their extrema, based on the maximum position, velocity, and acceleration limits in Tables 7 and 8 for the heave direction. Only points underneath both the position and velocity curves are permissible combinations of the parameters. Heave was the limiting degree of freedom.

Table 8: Velocity and Acceleration Limits of CAREN Platform

DOF	Max. Velocity	Max. Acceleration
Heave	+/- 0.30 m/s	-4.9 m/s^2, 6.9 m/s^2
Pitch	+/- 30º/s	+/- 500º/s^2
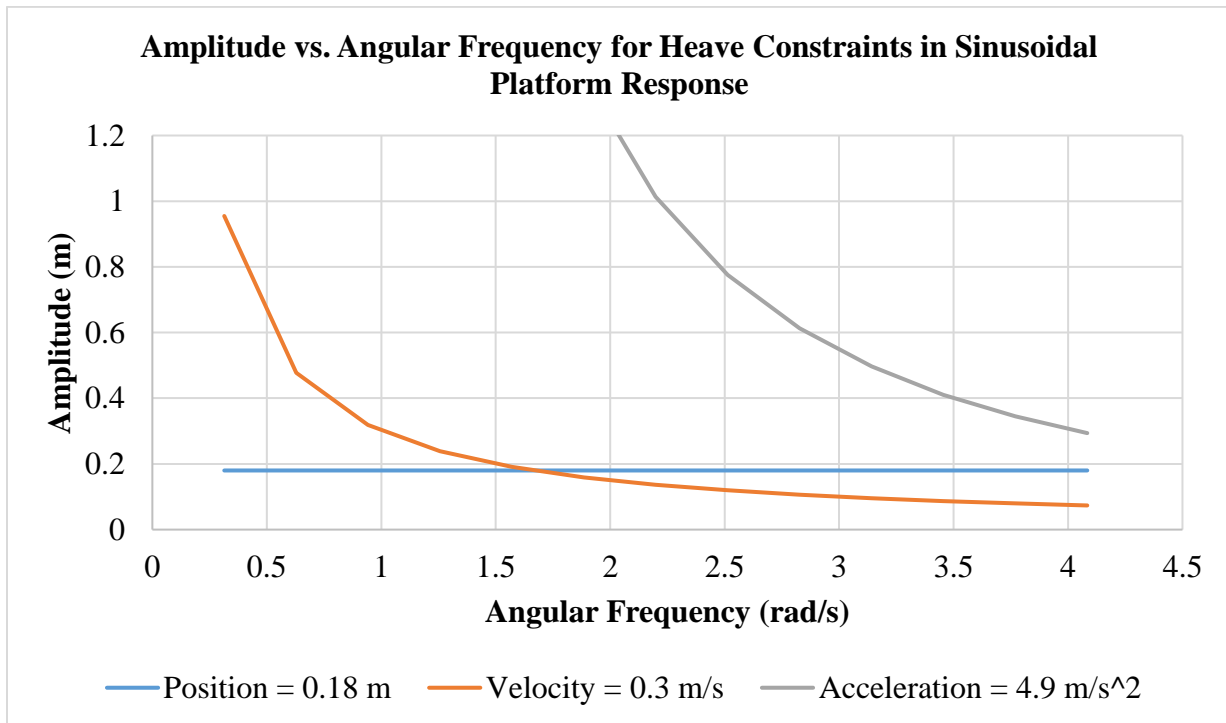
Figure 7: Limiting Curves for Sinusoidal Inputs to CAREN Platform

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Through experimentation with the CAREN system, coupled motion limitations were found for the maximum and minimum heave excursion while the pitch angle was at varied degrees used in the research. After these limits, the pitch angle will decrease to zero as the heave displacement approaches the maximum of +/- 0.18 meters noted in Table 7. Figure 8 shows an example graph of this experimentation and Table 9 provides the approximate values for these coupled motion limitations. The limiting magnitude between two trials per pitch angle is provided.
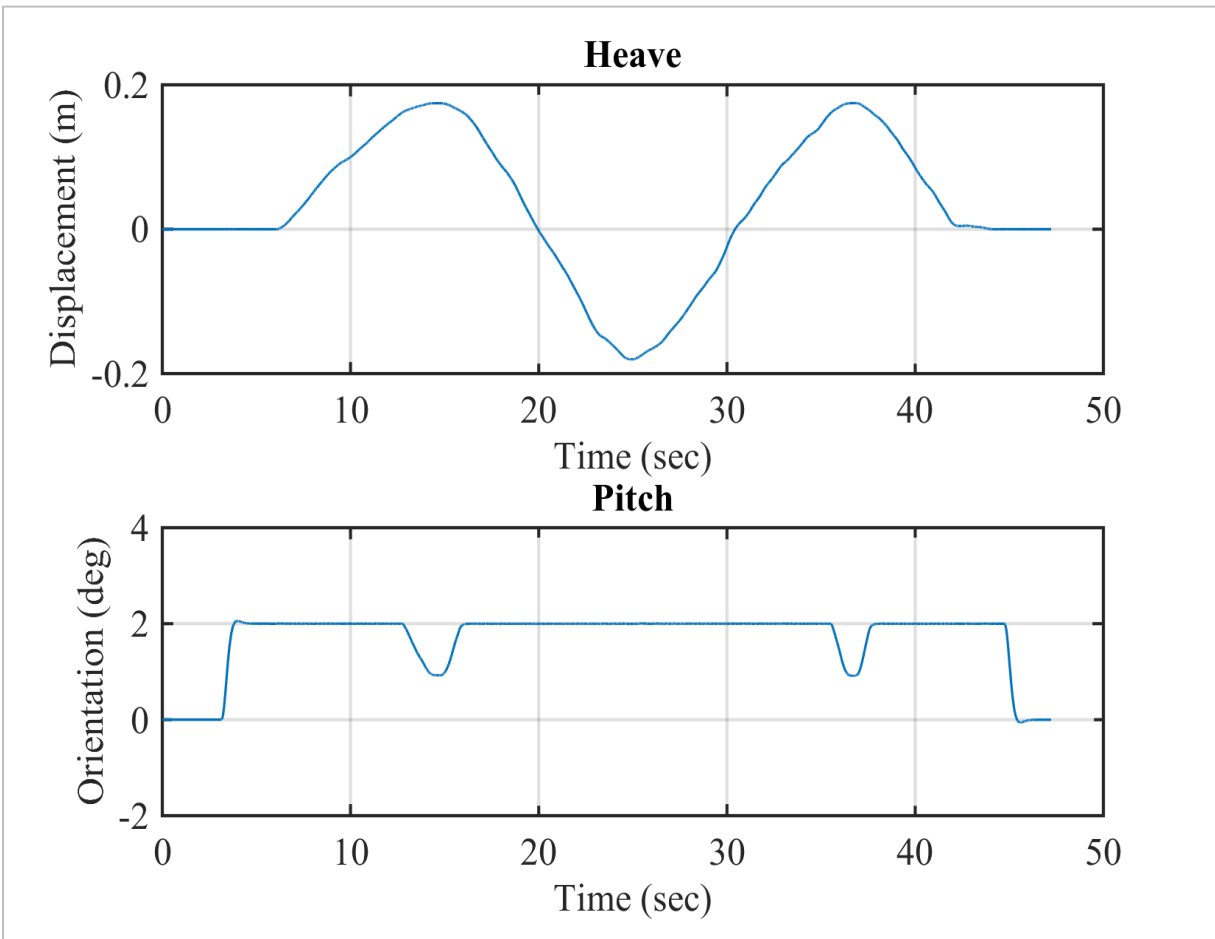
Figure 8: Coupled Heave and Pitch Limits Test for Pitch Set to 2 Degrees. Platform Moved Manually in Heave and Effect on Pitch Observed.

Table 9: Heave Excursion Limitations for Coupled Heave and Pitch Platform Motion

DOF	Max. Excursion
Heave at Pitch = +0.5 deg	+ 0.1691 m / - 0.1801 m
Heave at Pitch = +1 deg	+ 0.1716 m / - 0.1801 m
Heave at Pitch = +2 deg	+ 0.1613 m / - 0.1801 m
Heave at Pitch = +3 deg	+ 0.1508 m / - 0.1774 m

Note that from $+3^o$ and greater, the maximum excursion in the negative (downward) platform direction encounters limits. Negative pitch angles impose a similar but opposite result to Table 9, where heave can almost reach the full excursion in the positive direction but not the negative direction.

5.1.3 Force Plates

Two ForceLink (Motekforce Link, Amsterdam, Netherlands) force plates, with high accuracy strain gauge load cells, are on the platform directly under the split belt of the treadmill. Combined with the data acquisition software described in Chapter 6, D-Flow, the force plates measure ground reaction forces, moments, and center of pressure at each foot. The force plates have a resolution of +/- 0.5 N and a center of pressure sensitivity less than 2mm with loads under 1000 N. The data sampling rate from the force plates during the research was 300 Hz by default.

5.1.4 Motion Capture

Integrated with the CAREN system is a Vicon motion capture system (Vicon, Oxford, UK) comprised of ten Bonita B10 infrared emitting cameras surrounding the environment. The system tracks passive retro-reflective markers placed on a person and/or equipment in the capture volume. The B10 cameras capture up to 250 frames per second (fps) with 1-megapixel resolution. Motion capture during the research was set to the default of 100 Hz (fps).

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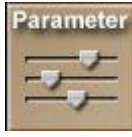
CHAPTER 6: EXPERIMENTAL DESIGN SOFTWARE

6.1 D-Flow

6.1.1 Overview and Modules

D-Flow (Motekforce Link) is the control software for the CAREN system. It is comprised of a graphical user interface (GUI) which provides modules for capabilities like programming platform motion, establishing parameters which can be inputs or buttons on the operators tab in the control window, adjusting settings for motion capture, creating display graphics, and manipulating/saving data. Users create an application comprised of interconnected, and sometimes standalone, modules. The key modules used in this research are described in Table 10.

Table 10: D-Flow Modules Used in the Research

Module	Purpose	Inputs	Outputs
Platform	To drive the motion base	Displacement trajectories in Cartesian coordinates (X, Y, Z, roll, pitch, yaw)	Platform motion
MoCap	To enable motion capture and force plate data collection	Settings relevant for motion capture	Raw marker trajectories and ground force, torque, and center of pressure
Parameter	To establish pre-set and adjustable parameters which provide inputs to the application	Pre-set parameter types and corresponding settings	Parameter settings: manually entered or activated (producing numerical outputs)
Generator	To compute a mathematical function for use in controlling the system or data analysis	Any numerical input from a set parameter, measurement, or another computation	The result of the function

6.1.2 Program Architecture

The D-Flow Application created for this research is described here. The program implemented the platform control, invoking the simplified responses outlined in Chapter 3, Theory, as well as meeting the data acquisition objectives. Figure 9 shows the overview of the program and can be referenced for visualization of the flow described in the text.
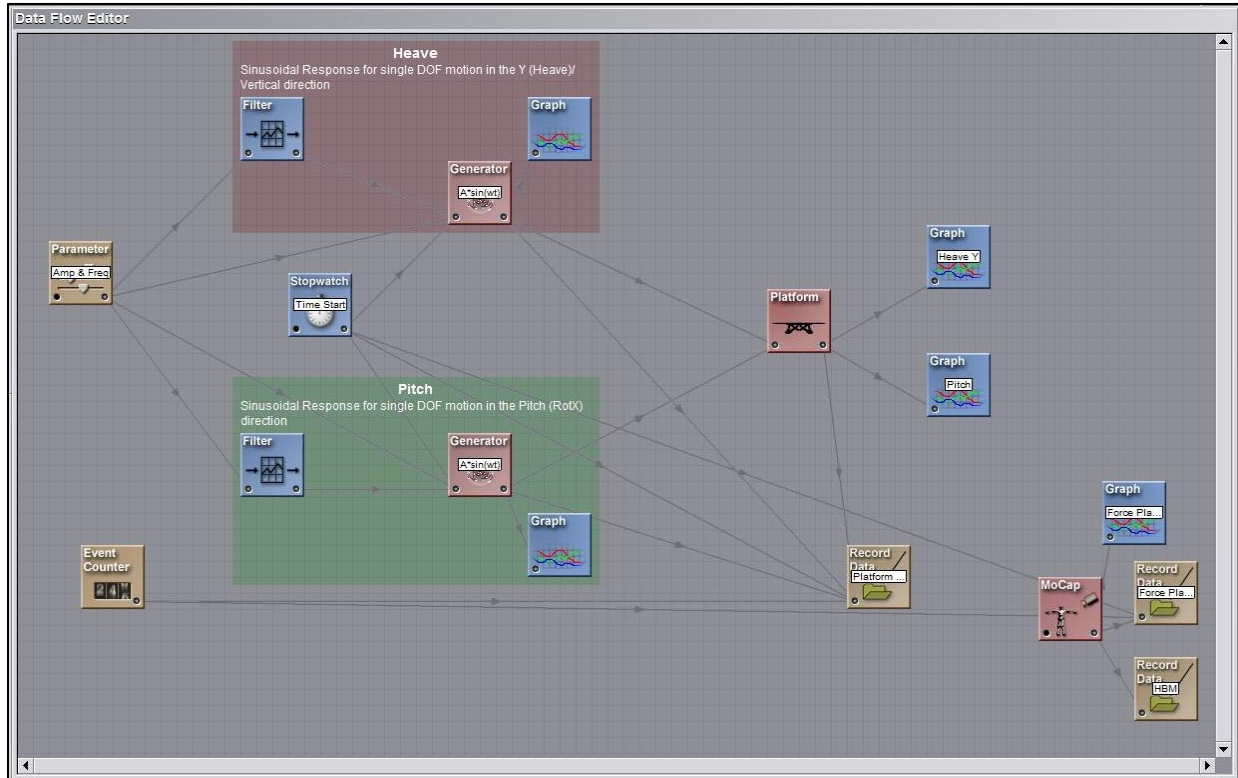
Figure 9: D-Flow Application

D-Flow's Runtime Console (Figure 10), where the application is controlled, was customized for this study. It included the functionality to enable/disable the programmed platform motion as a safety feature, parameter adjustment sliders/entry boxes with set limits also as a safety feature, and "Activate Motion" and "Stop Motion" buttons for easily accessible manual control of when the programmed motion starts and stops.

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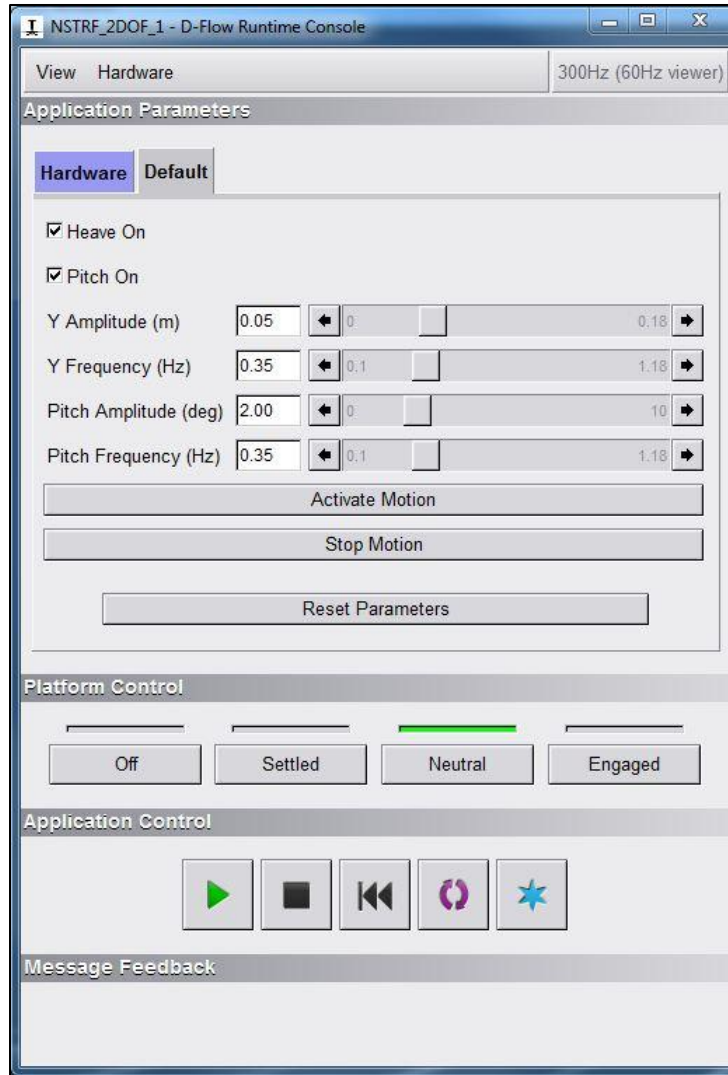
Figure 10: Runtime Console used to Operate Platform

These capabilities were instituted through the Parameter module window, Figure 11a. Checkbox type parameters had the default configuration set to "Unchecked" when the application and Runtime Console first open. Slider type parameters included maximum and minimum values associated either with platform motion limits or test design limits and a default of the minimum value for additional safety, as shown in Figure 11b. Button type parameters included specification of an event which would be triggered when the button was clicked on the Runtime Console, as shown in Figure 11c.

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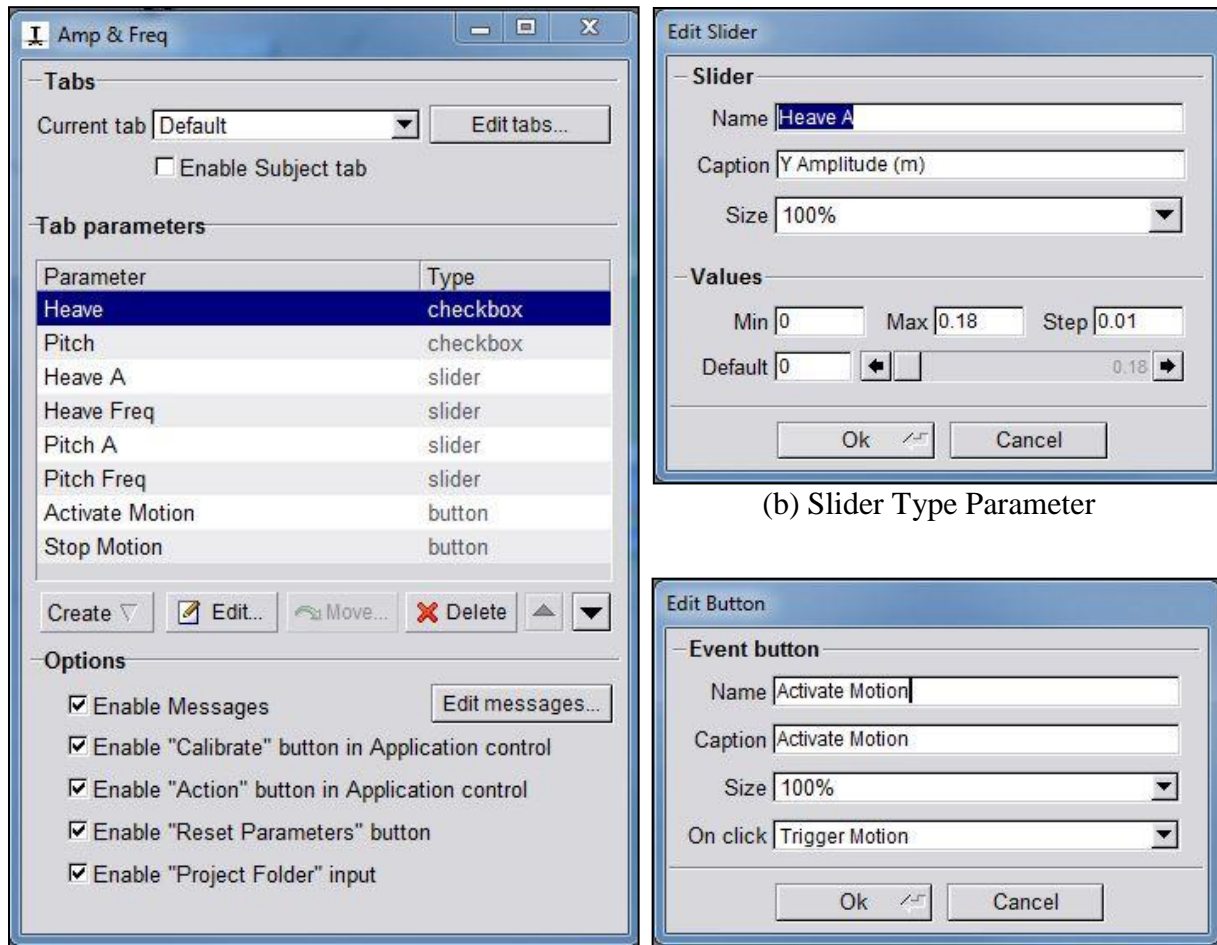
(a) Parameter Window   (c) Button Type Parameter

Figure 11: Parameter Creation

A Global Event, Figure 12, specifies an event which occurs when running the application or can be manually activated by the operator. Built-in events like Play, Stop, and Reset are triggered when the standard operation buttons are clicked in the Application Control area of the Runtime Console. Custom events were added and are activated by the custom buttons. These events are used as conditions for which a D-Flow module can initiate or end some process. Each module has a property window called "Actions" where actions such as "Play", "Stop", "Reset", or "Stop + Reset" can be attributed to each existing event. Figure 13 provides an example for how actions can be set for when an event is triggered.

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Figure 12: Global Events

Figure 13: Action Settings for Generator Module

The flow of this process is described via example as follows: The "Activate Motion" button activates the "Trigger Motion" event, refer back to Figure 11c. Then, specific modules, which have an action set to begin during the "Trigger Motion" event, perform the specified action. Figure 14 shows actions attributed to the "Trigger Motion" event, represented as yellow highlighted text on modules which use the event. Figure 15 shows the actions attributed to "Stop Motion".

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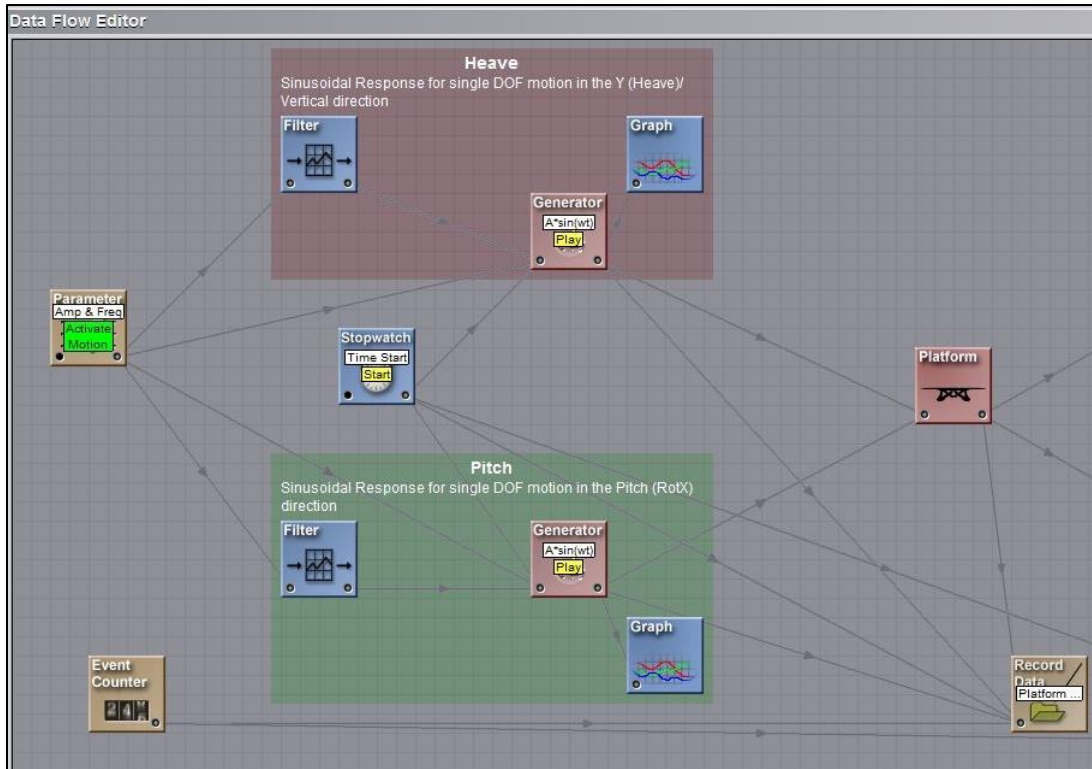
Figure 14: Actions Associated with the Trigger Motion Event
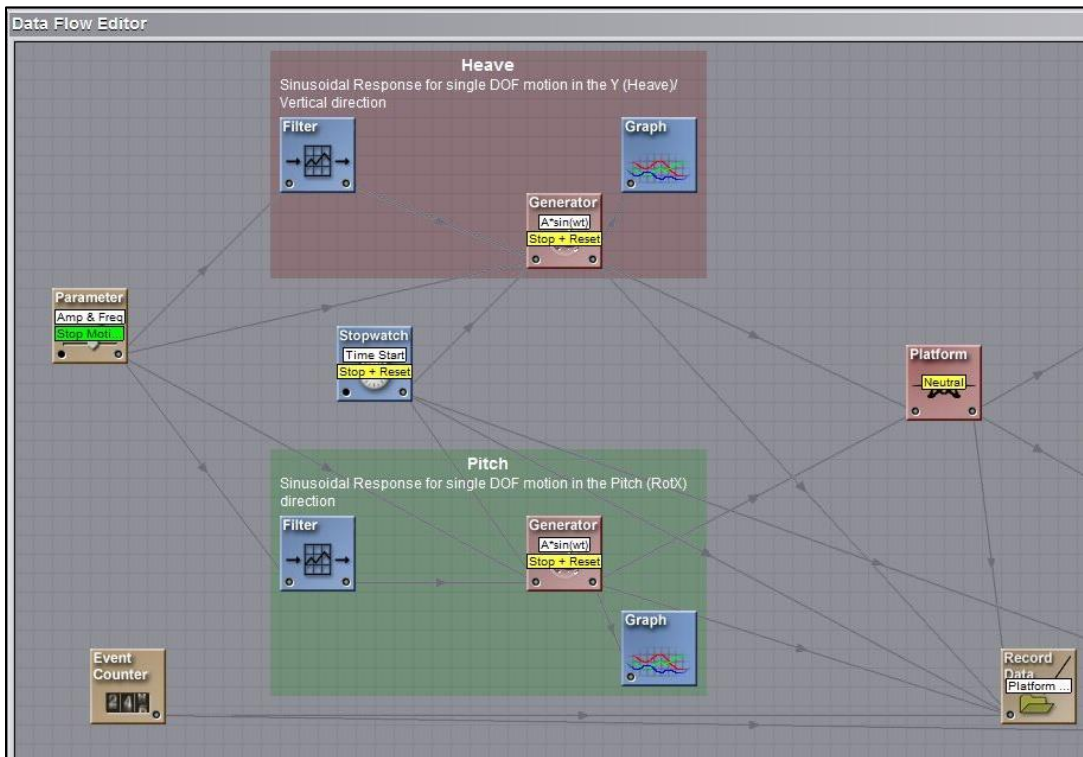
Figure 15: Actions Associated with the Stop Motion Event

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Some important features to note are that the Stopwatch does not begin until the "Activate Motion" button is clicked, so that Time (which is an input to the sinusoidal function which drives the platform motion) will always start at zero, and that the platform returns to Neutral when the "Stop Motion" button is pressed, enabling a smooth return to the platform's center (zero) position.

The generator module is where the sinusoidal responses are implemented, one for heave only (vertical displacement) and the other for pitch only (rotation about X). Two parameters, Amplitude (in meters) and Frequency (in Hertz), are inputs to the functions. With the input frequency in Hertz, Eqn. 2 is modified to convert frequency to angular frequency, as in Eqn. 6.

$$y(t) = A * \sin(2\pi f * t) \qquad \text{(Eqn. 6)}$$

The Amplitude and Frequency parameters of are of a slider type, meaning that they have the capability of being adjusted while the platform is moving. Although, adjusting real time is not applicable to the experimental test in this research, it was of interest during test development and may be of interest in future work. The caveat is that using the manual slider for frequency while the platform is moving generates noise to the command and can cause undesirable vibration. For this reason, a filter is placed on the frequency parameters before each is inputted to a generator. This filter was used to only limit the rate of change of frequency but not the steady state frequency input itself. The graphical inputs and outputs of the filter are displayed in Figure 16.
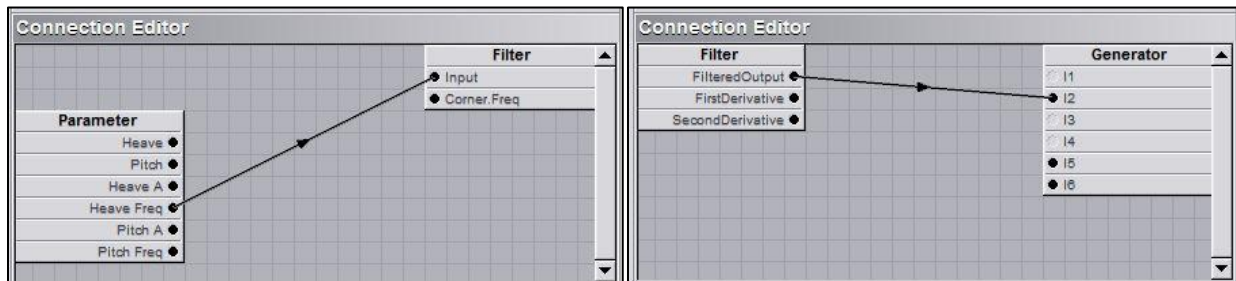
Figure 16: Connection Editors Showing Inputs and Outputs from Slider Parameter Filter

Figures 17 and 18 show the response implemented in the generator for heave and pitch, respectively. For the inputs in both cases, I1 is the amplitude in meters or degrees, I2 is the frequency in Hz which is then expressed in rad/s, and I3 is the time in seconds provided by the Stopwatch. A conditional if-then statement was used to test if the appropriate checkbox in the Runtime Console was checked for heave and pitch (causing the binary input parameter to switch to "1"). If so, then the response would be generated. Otherwise, the output will remain at zero.
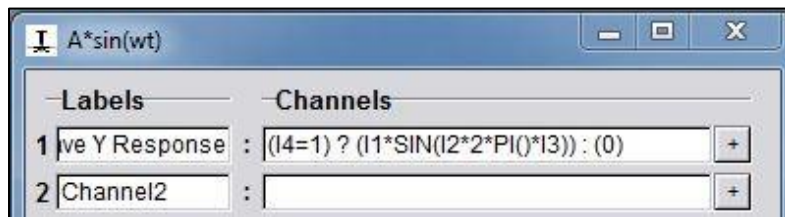
Figure 17: Heave Response Generator
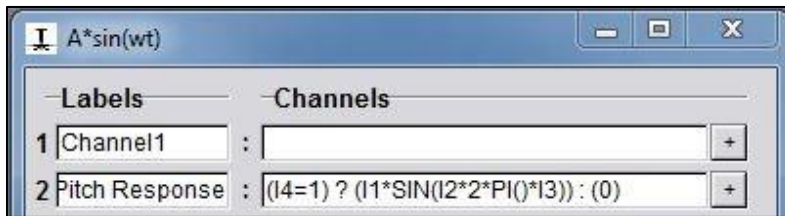
Figure 18: Pitch Response Generator

The outputs of displacement/orientation from the generators are connected to the appropriate DOF in the Platform module to control the motion. Figure 19 provides the example for heave, which is connected to the vertical DOF, PosY. The output from the generator for pitch motion is connected to RotX.
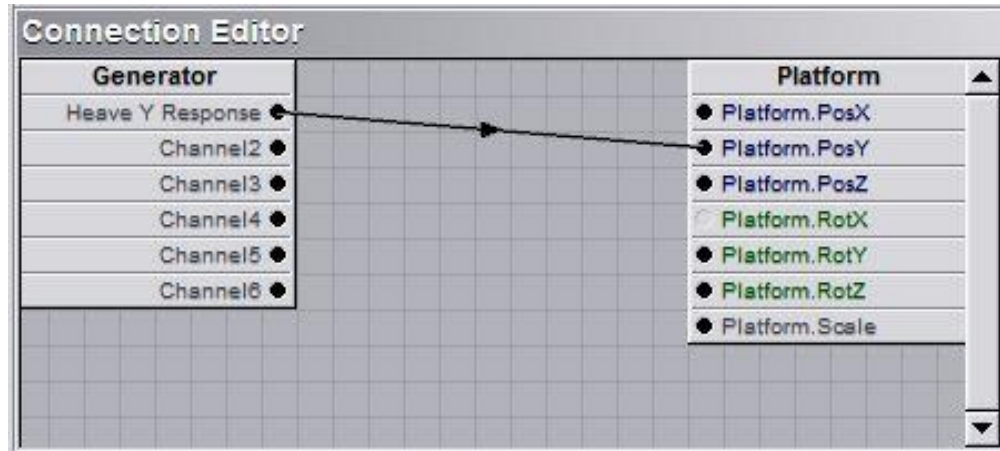
Figure 19: Heave Platform Input

Various graphs throughout the application provided real-time plots of the generated function, the platform motion, and force plate measurements. An example real-time graph for platform motion is shown in Figure 20a given the inputs in Figure 20b. In this example, the "Stop Motion" button was pressed at the peak in the third cycle, and the platform returns to its neutral, zero position.
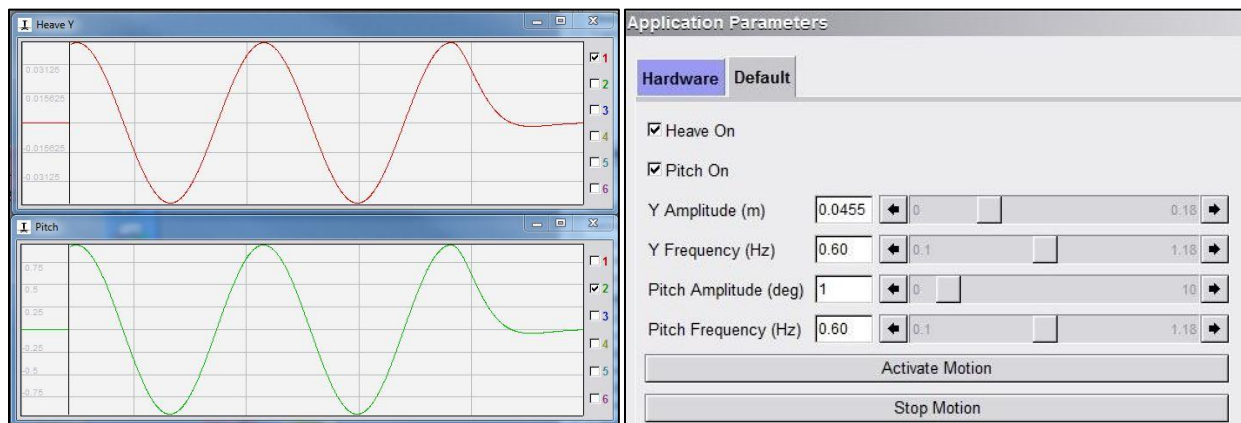
(a) Real time graphs of Platform motion   (b) Input parameters in example scenario

Figure 20: Example of Real-time Graphing Feature

The MoCap module provides various tabs for setting motion capture related parameters such as adding a biomechanical model and establishing the marker set, selecting outputs, etc. It also includes enabling/disabling of the force plates, the calibrate zero-level button for the force

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plates, and a low pass filter option for the measurements. There are also real-time display options for viewing the motion capture markers and for on-screen visualization of forces from each plate. These features were used for verification purposes but were disabled during human subject collection so as to not distract participants. D-Flow's "DRS Window", a default 3D environment, was displayed on the projection screen from a perspective which provided participants with a grid they could focus on, if needed, but where edges were visible in peripherals. This can be seen in Figure 5 showing the full CAREN system.

Channels from the modules were connected to Record Data modules. Platform position trajectories, in Cartesian Coordinates (all 6 DOFs), were written to file. All force plate data for each force plate were written to file as well. Both the platform data and the force plate data were recorded at a default of 300 Hz. An Event Counter was connected to the "Activate Motion" and "Stop Motion" buttons. Each time they were pressed, the count would increment by one. This information was also recorded in the platform and force plate files and were useful for parsing the trial during data processing. Motion capture data were also recorded in D-Flow, but it relied on real-time labeling of markers and so was not used for the analysis. It was simply saved as a backup to the recording made directly in the motion capture software (see section 6.2). All Record Data files were set to append, which helped automate the file naming process (as the appended number matched the trial number).

6.2 Vicon Nexus

The motion capture software used for this research, and paired with the CAREN system, was Vicon Nexus (Vicon, Oxford, UK), Version 2.5. The routine procedures were followed for each collection which included camera calibration, masking artifacts (reflections), setting the origin, and creating a Subject with session folders. This research used the Human Body Model

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(HBM) (Even-Zohar and van den Bogert 2009) marker set and skeletal model recommended for the CAREN system, as shared in 7.3.3 Marker Placement. Using the HBM can provide additional capabilities when enabled through D-Flow's MoCap module including real-time joint kinematics and kinetics as well as estimated muscle forces [26]. In this research, using the HBM marker set allowed for ease of post-processing in Nexus. Using the model also provided the ability to perform analysis directly in Nexus such as obtaining the joint angles shared in Chapter 9, Results. More information regarding use of Vicon Nexus is shared in the subsequent chapters.

CHAPTER 7: EXPERIMENTAL DESIGN IMPLEMENTATION

7.1 Overview

The human subject study underwent approval by USF's Institutional Review Board (IRB). A copy of the approval letter is provided in Appendix A. Subjects performed standing squat and row exercises without external resistance, engaging in motion that would be seen when using a cable driven EED.

7.2 Subjects

7.2.1 Inclusion Criteria

Based on inclusion criteria in previous research studies at CARRT and the needs of this research, minimum subject inclusion criteria were determined, approved by the IRB, and advertised. The required criteria to qualify for this study were that the volunteer must:

1. Be between the ages of 18 and 65 years old

2. Have no physical impairments

3. Be able to complete exercise motions such as squats and vertical rows

It was also of interest to follow design criteria used by NASA for flight crew interfaces, specifically the average anthropometrics for a 40 year old American male to the 40 year old Japanese female (5th to 95th percentile) [27]. However, deviations from these anthropometrics would have been accepted in this study.

7.2.2 Subject Selection

A total of four subjects were selected for this study, specifically the first four to volunteer. It was important that all participants had prior training in performing the exercises in this study, or at least similar ones. This was because spaceflight crews have extensive training and instruction for completing exercise, so a comparable able-bodied subject group was desirable. This was also of interest for consistency of exercise, where an individual's variations across exercise cycles could be distinguishable from variations due to the conditions being tested. All subjects had qualified experience with a combination of gym training, team sports participation, background knowledge in exercise science or biomechanics, and resistive and aerobic workouts 3-7 days per week. Attributes such as age, gender, height, and weight pertaining to subjects selected for this study are included later in Table 14 in Section 9.1 Subject Parameters.

7.3 Protocol

Each subject participated in one session, lasting for approximately two hours. They completed the squat and row exercises, described in 7.3.1 System Setup and Subject Preparation, with the Static and Dynamic platform conditions described in 7.3.4 Experimental Trials. Additional details regarding a test collection are provided throughout this section.

7.3.1 System Setup and Subject Preparations

Prior to a test session, the CAREN system was prepared according to standard procedures. The motion capture system was calibrated and volume origin set. The force plates were zero leveled. A video camera was setup as well. Subject session folders were created for the data acquisition. The DRS Window projected on the panoramic screen was adjusted to a tilted view as was described in 6.1.2 Program Architecture.

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Upon subject arrival, a description of the test was provided in accordance with IRB procedures. Subjects then read and signed an informed consent document. Participants also signed a photo/video release. Next, subjects were provided with further instruction on the exercises to be completed as shared in Table 11.

The descriptions for the Squat were adapted from the Johnson Space Center (JSC) Resistive Exercise Document (JSC 29558) [28]. The squats in this study are similar to conventional front squats and goblet squats. The Rowing descriptions were associated with performing the rowing cycle on a seated rowing ergometer. However, this was translated to a "standing row", where the motions should be comparable but may differ from the seated configuration because a constraint is removed (the seat) and the body weight must be supported by the feet in this 1G testing. There is also a tendency to want to stand straight up in each cycle, whereas you would not lay down when using a rowing ergometer. This issue was brought to the attention of participants and they were instructed to reproduce motions as close to rowing machine use as possible. The standing row, simply referred to as "Row" throughout the remainder of the thesis, was expected to be an unconventional exercise for any participant so appropriate time was given for the participants to practice until they felt comfortable.

Additional instruction and critique of form was provided on an as needed basis if, for example, the participant had further questions or if some part of the original instruction was not followed. Demonstrations were given while instructing. Videos of MED-2 use were shown as well to provide a reference for what these exercises relate to and the purpose behind the research.

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Table 11: Instruction Provided to Subjects Regarding Exercise Form

Exercise	Instruction
Squat	Stand with feet shoulder width apart. While squatting, maintain a flat back, chest out, with head upright and straight forward. Bend until thighs are parallel to floor (knees at 90°). Try to flex and extend hips and knees at the same rate. Try to keep motion continuous (fluid, without pausing long after standing/squatting) and keep consistent. Keep arms in front of torso with palms facing toward you (imagine holding a bar/ can close hands), in a comfortable position.
Row	Imagine you are using a rowing machine/ ergometer. Stand with feet shoulder with apart. Find an appropriate spot to gaze at (comparable to cable position on a rowing ergometer relative to your body). The cycle will be: Recovery, Catch, Leg Drive, Finish, Hands Away, and Body Over. Consider how far back you may lean if you were using a rowing machine and try to set this as a fixed point for the Hands Away part of the cycle (how far you stand up).

Descriptions for exercising while on the platform in the Dynamic setting (while moving), were also provided as shown in Table 12. Participants were informed of the key concept of trying to minimize the movement of their center of mass. This meant that when they squat/bend down, the platform will move up. When they stand/straighten out, the platform will move down. The cause and effect is not critical in this case since the human is not driving platform motion in this research. Hence, the instruction was for the participant to squat when the platform moved up and straighten when the platform moved down. An example human-VIS interaction simulation, provided by NASA's Digital Astronaut Simulation group, demonstrated the center of mass of the person remaining relatively stationary during rowing while the platform moved.

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Participants were also instructed to try and "match" the platform motion. This connects back with the Frequency Matching measure. To provide the best chance of matching the platform within the first exercise cycle or two, participants were given a starting form coinciding with the part of the cycle that the platform begins moving. They were also provided a warning of when the platform would start[2].

Table 12: Instruction Provided to Subjects Regarding Exercise on Platform

Exercise	Prior to Trial Start	Trial Start/ Platform Starts Moving	While Platform is Moving
Squat	Start with knees slightly bent	Continue to a squat when the platform starts moving	Match platform motion
Row	Start with knees bent, arms straight, and body over	Complete row to recovery stage	Match platform motion

The stages of platform and exercise motion are depicted in Figures 21 and 22, demonstrating what constitutes matched (i.e., synchronized) motion.

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[2] Operator asked participant, "Ready?" and once they entered the starting position and said "yes", the operator warned of the platform motion activation with "And Go".

Figure 21: Stages of Squat Exercise with Dynamic Platform in Heave Condition

Figure 22: Stages of Row Exercise with Dynamic Platform in Heave Condition

7.3.2 Pre-Test Measurements

Prior to the Experimental Trials, subject measurements were recorded. Height and weight were measured from a weigh beam physician scale. Those measurements are presented in Table 14 in 9.1 Subject Parameters.

A baseline amplitude and baseline frequency, as introduced in 4.3 Frequency Selection, was determined for each participant via off-platform measurements as well. Height difference while completing a squat was measured as a rough estimate of the maximum amount their center of mass might move in the vertical direction while completing the exercise. Subjects did not feel their row height difference would be significantly different, so the same measurement was used for each subject for rowing. To determine a Dynamic platform response amplitude which was individualized for each subject, "Baseline Amplitude", a value was selected based on this height difference. Specifically, an order of magnitude in reduction from the height difference was used. This provided an amplitude which was well within platform limits, yet had a quantifiable relation to the subject motion. This approach, compared to alternatives, is further discussed in 10.2 Limitations and Future Improvement. The Baseline Amplitude, shared for both squats and rows, is presented for each subject in Table 15 in 9.1 Subject Parameters.

For "Baseline Frequency", each subject's practiced, comfortable squat and row rates were measured. Subjects performed 5 repetitions of squats off-platform while being timed via stopwatch. Squats per second was then calculated from those 5 repetitions to obtain a Baseline Frequency. The same process was completed for finding Baseline Frequency for rowing. These baseline measurements are presented in Table 15 in 9.1 Subject Parameters.

7.3.3 Marker Placement

Just prior to marker placement, subjects donned a full-body harness which was tightened adequately but not so much as to restrict squat or rowing motion. Subjects performed exercise to ensure it was set comfortably. As mentioned in 6.2 Vicon Nexus, the HBM marker set (47 markers) was used for motion capture. Retroreflective markers (14 mm) were placed on bony anatomical landmarks (i.e., aligned with joint centers) and on other body segments, depicted in Figures 23 and 24. Most markers were secured using double-sided adhesive directly to the skin and tight clothing. Head markers were on a headband and foot markers were secured to the subject's athletic shoes. Pelvic markers were on a waistband which was wrapped around the outside of the full-body harness. Four markers were also placed on the motion platform in case the location of the subject relative to the platform edges were required for analyses. The platform markers may also aid future modeling, where motion tracking of the platform surface may be more helpful than the trajectory of the center of the platform.

Figure 23: Markers Placement

Marker	Marker Name (Extended)
LHEAD	Left head
THEAD	Top head
RHEAD	Right head
FHEAD	Forehead
C7	C7
T10	T10
SACR	Sacrum bone
NAVE	Navel
XYPH	Xiphoid
STRN	Sternum
BBAC	Scapula
LSHO	Left shoulder
LDELT	Left deltoid
LLEE	Left lateral elbow
LMEE	Left medial elbow
LFRM	Left forearm
LMW	Left medical wrist
LLW	Left lateral wrist
LFIN	Left fingers
RSHO	Right shoulder
RDELT	Right deltoid muscle
RLEE	Right lateral elbow
RMEE	Right medial elbow
RFRM	Right forearm
RMW	Right medial wrist
RLW	Right lateral wrist
RFIN	Right fingers
LASIS	Pelvic bone left front
RASIS	Pelvic bone right front
LPSIS	Pelvic bone left back
RPSIS	Pelvic bone right back
LGTRO	Left greater trochanter
LLM	Left lateral malleolus of the ankle
LTOE	Left toe
RGTRO	Right trochanter major of the femur
RATI	Right anterior of tibia
RLM	Right lateral malleolus of the ankle
RHEE	Right heel
RTOE	Right toe
RMT5	Right 5th meta tarsal

Figure 24: Human Body Model Motion Capture Marker Set

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7.3.4 Experimental Trials

A list of the experimental trials and the associated parameters are provided in Table 13. In all experimental trials, the subject stood in the center of the CAREN motion platform. The experimental trials began with a "T-Pose" for the Static Calibration and was followed by isolated Range of Motion exercises for a Dynamic Calibration. The terms Static Calibration and Dynamic Calibration refer only to human subject calibration for motion capture and should not be confounded with Static and Dynamic platform motion. There are also "Baseline Squat" and "Baseline Row" trials. These are not the off-platform measurements, but rather occur on the platform so that motion capture and force plate measurements can be recorded. To clarify, the platform remains static during the Baseline Squat and Baseline Row trials. All trials labeled "Squat" include vertical, heave, Dynamic platform motion, with a sinusoidal response of baseline amplitude and various frequencies. All trials labeled "Row" have the same heave only trials, but also combined heave and pitch trials with the parameters specified in the Experimental Trials table.

During the trials, the subject's harness was hooked to the CAREN safety cage. Enough slack was left for exercise motion to be un-restricted, but tight enough to prevent walking off the platform edge or falling. Subjects were offered the opportunity to take a break after the subject calibration trials and after the squat trials. However, some participants opted to continue straight through the trials. All participants completed Trials 1-16. Some participants chose to complete the extra trials with remaining time in the session. These extra trials included pitch angles greater than three degrees and also heave and pitch at dissimilar frequencies. Data from those trials were not analyzed as part of this research but may be included in future work.

Each trial listed in Table 13 was completed once. There were several instances where trials were re-started at the subject's request or if there were an operational issue with file naming or the

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like. This is not reflected in the Results, so for all practical purposes, there was one recording for each trial. Each trial included 5-10 exercise cycles (repetitions).

Table 15 should be referred to for the Baseline Measured amplitude and frequency inputs to the Experimental Trials table below.

Table 13: Experimental Trials and Associated Platform Settings

#	Exercise	Heave Frequency (Hz)	Heave Amplitude (m)	Pitch Freq (Hz)	Pitch Amp (deg)
1	Static Calibration	N/A	N/A	N/A	N/A
2	Dynamic Calibration	N/A	N/A	N/A	N/A
3	Baseline Squat	N/A (Static)	N/A (Static)	N/A	N/A
4	Squat	0.10	Baseline Measured	N/A	N/A
5	Squat	0.35	Baseline Measured	N/A	N/A
6	Squat	0.60	Baseline Measured	N/A	N/A
7	Squat	Baseline Measured	Baseline Measured	N/A	N/A
8	Baseline Row	N/A (Static)	N/A (Static)	N/A	N/A
9	Row	0.10	Baseline Measured	N/A	N/A
10	Row	0.35	Baseline Measured	N/A	N/A
11	Row	0.60	Baseline Measured	N/A	N/A
12	Row	Baseline Measured	Baseline Measured	N/A	N/A
13	Row	Baseline Measured	Baseline Measured	Baseline Measured	0.5
14	Row	Baseline Measured	Baseline Measured	Baseline Measured	1
15	Row	Baseline Measured	Baseline Measured	Baseline Measured	2
16	Row	Baseline Measured	Baseline Measured	Baseline Measured	3
17	Row (extra)	Baseline Measured	Baseline Measured	Baseline Measured	4
18	Row (extra)	Baseline Measured	Baseline Measured	Baseline Measured	5
19	Row (extra)	Baseline Measured	Baseline Measured	Baseline Measured	6
20	Row (extra)	Baseline Measured	Baseline Measured	0.35	2
21	Row (extra)	Baseline Measured	Baseline Measured	0.60	2
22	Row (extra)	0.60	Baseline Measured	0.35	2

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Since participants did not undergo prior training for exercise on the CAREN system, it was considered that a "ramp-up" approach for the trials was most appropriate. Each participant completed the trials in the order provided in Table 13. Though, in other research, trials are usually randomized for statistical analysis purposes, there was a greater interest in making the experience consistent across all subjects in this case because of the learning/adaptation period. If a participant were to start at the highest frequency of exercise, their performance may be affected more so by the surprise of the fast moving platform rather than the movement itself. In other words, the ramp-up approach allows time to acclimate and be able to better anticipate the movement. To also help in this regard, participants were given a practice period (roughly 10 platform cycles) at their baseline frequencies prior to the 0.10 Hz trials. They were welcome to stand and sense the platform motion and/or engage in practice exercise.

7.3.5 Questionnaire

A questionnaire was given to each subject following the experimental trials. They were able to provide insight into their personal exercise experience and provide feedback on the trials. Portions of the questionnaire specific to the squats and rows included four statements with a 5-point Likert Scale from Strongly Disagree to Strongly Agree. These ratings are presented in the Results. The questionnaire also inquired about the subject's exercise experience (frequency of exercise, resistive/aerobic exercises completed, and when/how trained) as well as general feedback about the study. A blank questionnaire is provided Appendix B. Extended responses are provided in Appendix C.

CHAPTER 8: DATA PROCESSING AND ANALYSIS

8.1 Kinetic Data Processing

A script was written in MATLAB R2014B (The MathWorks, Natick, MA) to process the Force and Platform data. This script is included in the Appendix E. The primary stages of the processing are described here.

8.1.1 Data Extraction

All Force Plate and Platform data were loaded into the script from the D-Flow saved data text files. For force plates, this included Center of Pressure, Force Components, and Moments for each of the two force plates. For platform, this included trajectories for all 6 DOFs and also the generated heave and pitch inputs to the platform. Both data sets also included the Timer and Event Counter increments from the D-Flow application. For the data analysis portion, the Y components of force and platform motion were of most interest. Hence, those column vectors were extracted and stored for extended processing. Figure 25 provides an example for all force components from one force plate.
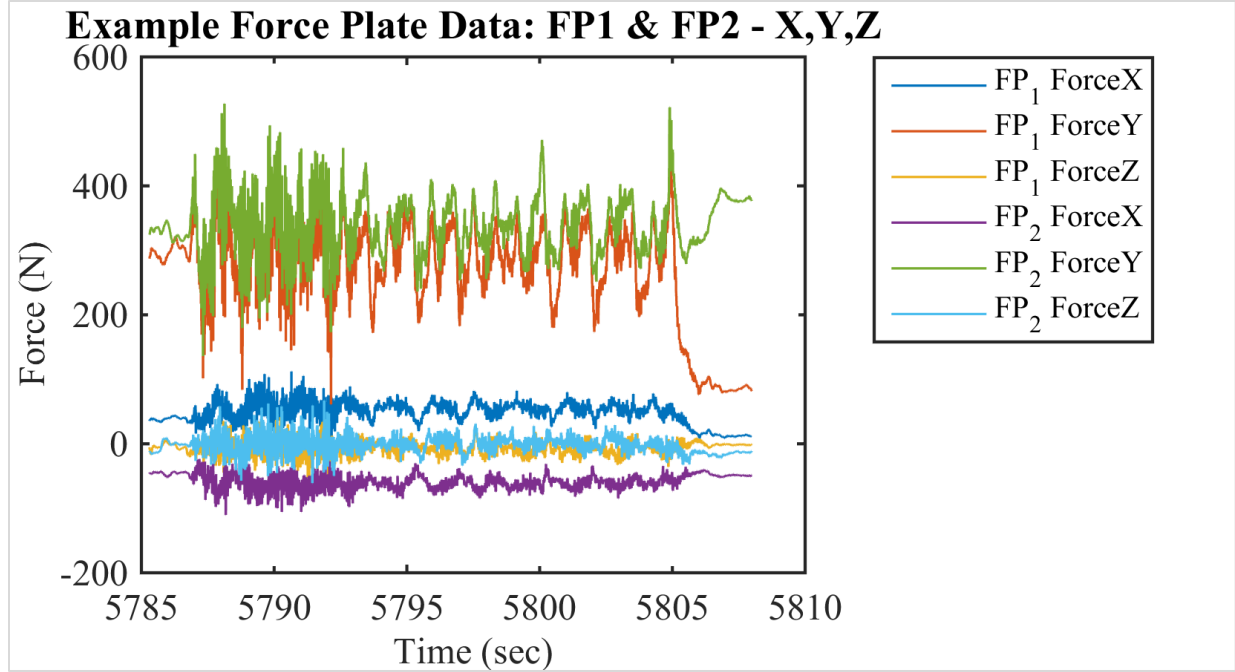
Figure 25: Example X, Y, Z Force Component Data from Two Force Plates for Squats

8.1.2 Filtering

A 3rd order Low-Pass Butterworth filter was used to remove high frequency noise. A cutoff frequency of 6 Hz was low enough to remove high frequency platform noise but high enough to not affect the amplitude of the major peaks associated with ground reaction force. In the Butterworth filter function in MATLAB (The MathWorks, Inc.), the cutoff frequency input is normalized to the Nyquist frequency. In this case, the sampling frequency of the force data was 300 Hz. Eqn. 7 shows the normalized cutoff frequency (W_n) calculation, where f_c is the desired cutoff frequency and f_s is the sampling frequency. Figure 26 shows the produced magnitude and phase responses of the filter.

$$W_n = \frac{f_c}{\frac{f_s}{2}} = \frac{6\ Hz}{150\ Hz} = 0.04 \qquad \text{(Eqn. 7)}$$

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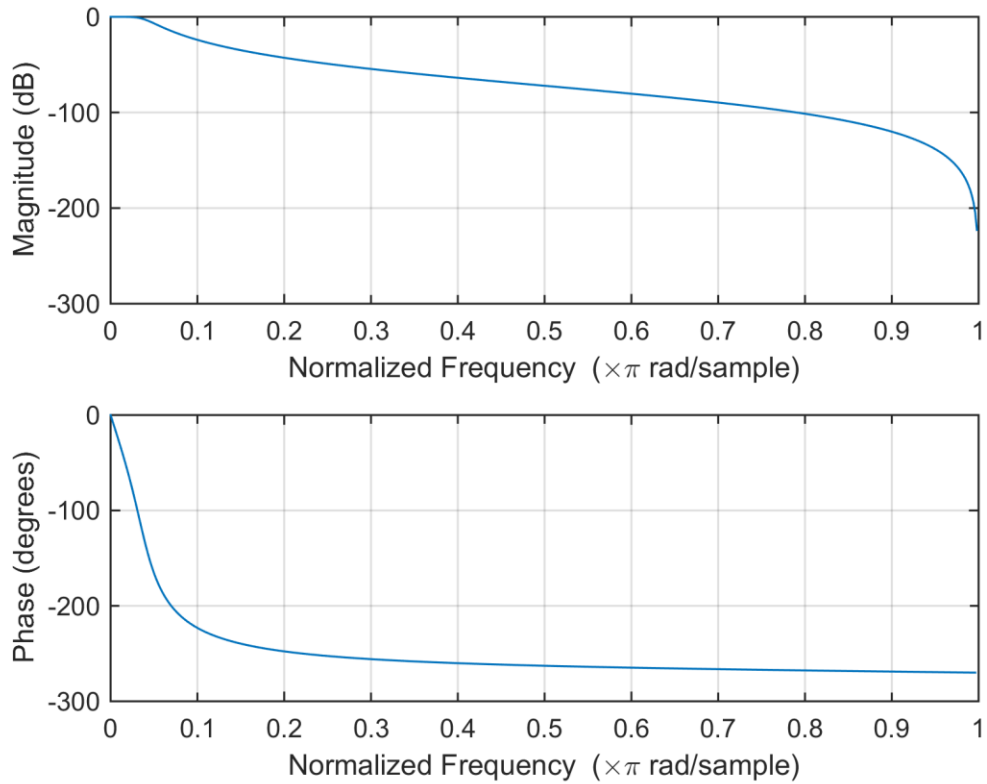
Figure 26: Magnitude and Phase Response for the Butterworth Filter Transfer Function

Figure 27 shows the result of applying the Butterworth filter on resultant force data. It also includes an example of data lost if a lower cutoff frequency were chosen.
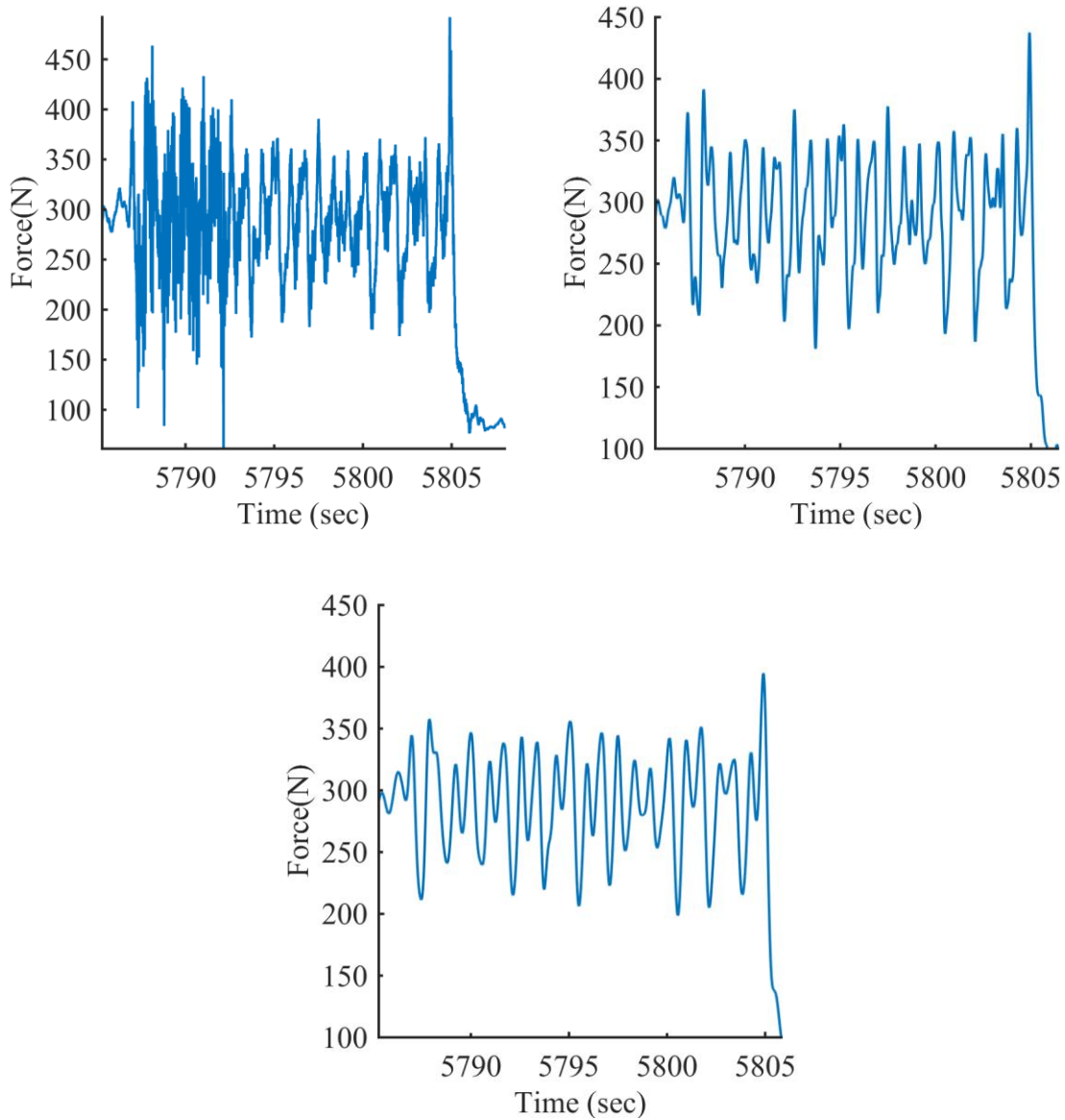
Figure 27: Resultant Force Filtering Example. Unfiltered Data (Top Left), Data Filtered at 6 Hz (Top Right), Over Filtered Data at 2 Hz (Bottom).

8.1.3 Computations

Resultant Force was computed as follows. Combining the loads from the two force plates into a single force simply required adding the component of interest, Force in Y (ForY) in this case, from force plate 1 and force plate 2. This was carried out for each element in the vector (force at each point in time). This new resultant force vector was then used for the remainder of the

analysis. In the script, each force plate was filtered first and then combined, but it is noted that the result was the same if adding first and then filtering. Example ForY data for each force plate and the resultant force of the two is shown in Figure 28.
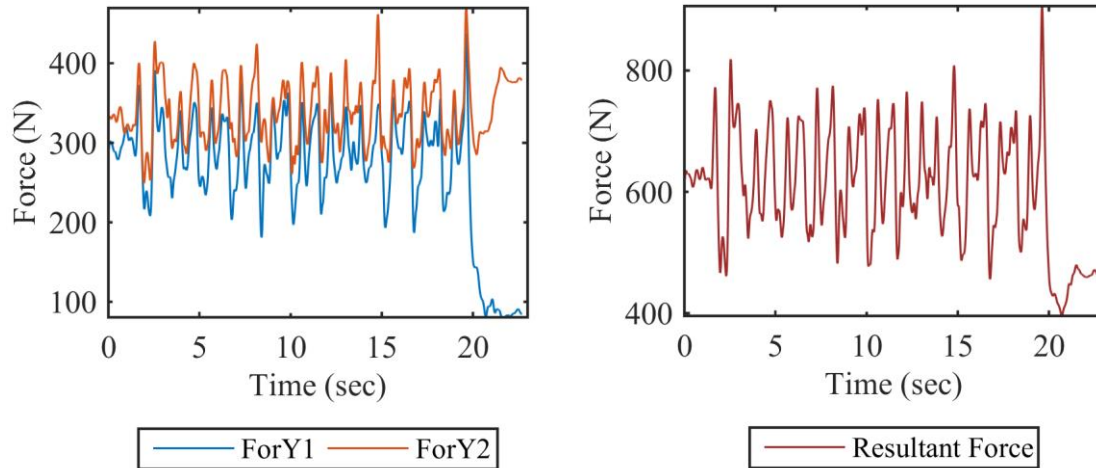
Figure 28: Force Component From Each of Two Force Plates (Left) and Combined Resultant Force (Right) for Example Squats.

Also note that since the subject's loads were distributed between two force plates, and given that no subject weight was distributed to the harness or handrails, the total Y component force due to exercise and platform motion is accounted for in the ForY data.

Average Force Range and Average Maximum Force were computed as follows. In order to find the range of force for each cycle, as well as the average of the maximum forces, first the peaks and troughs in the data needed to be identified. The "findpeaks()" MATLAB function was used to find points where neighboring elements were smaller (i.e., a "peak"/maxima). In order to find the troughs, the response was inverted to find the location in the vector at which the points occur, and then the appropriate data at those locations were extracted from the force data. An additional parameter, "peak prominence", was included in the findpeaks() function to allow only extrema with a peak height (force magnitude) of at least 50 N to be included. Smaller peaks were less consistent across cycles, trials, and subjects, so these were considered not to be attributed to

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the core exercise. The Average Maximum Force could then be found by averaging the magnitudes of the peaks (troughs excluded in this case). Then, Force Range was found for each individual peak-trough cycle. To elaborate, Force Range was a vector of the difference in magnitude between each corresponding peak and trough (element-by-element).

Force Frequency Matching was computed as follows. Effort was made to quantify the frequency of each exercise cycle of the force data which would quantify how well the subject matched the frequency of the platform motion. It was assumed that there were two prominent peaks per exercise cycle (which also corresponds to one cycle of platform motion), though it was found that in some cases there could be as many as four peaks or more. The two peak assumption did not apply to the 0.10 Hz trials. It was also not applicable to all subjects in all trials, so individualization would be needed for each case. Still, force frequency was estimated by finding the times at which extrema occurred, calculating the average period and accounting for the assumed two peaks per exercise cycle, and then inverting to find frequency. Further verification is needed, so the Estimated Force Frequency Matching is included in Appendix D rather than in the reported Results. The Table also provides some insight into why trials most likely require individualization. It does so by providing the number of ForcePeaks (FPks), from which the frequency was estimated, as well as the number of Platform Peaks (PPks). With the assumption that there should be about two force cycles for every platform cycle, FPks should be twice PPks in order to obtain a better estimate. It should also be noted that determining the frequency of the force by the method described here does not provide insight to any phase shift of that frequency from the platform motion frequency. In the future, additional signal analysis techniques could be applied to better assess the frequency of the forces. Frequency Matching is still presented in the results via graphs which provide visualization of how the force data aligns with platform motion. One can observe

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how well peaks and troughs match through study of the time synchronized plots. Further data manipulation which relates to parsing, normalizing, and graphing data is presented in 8.3 Description of Results Presentation.

8.2 Kinematic Data Processing

8.2.1 Cleaning and Pipelines

Motion capture was processed in Vicon Nexus. The trials of interest (Static and Dynamic baseline trials for squat and row for each subject) were cleaned and processed. Cleaning involved fixing swapped marker labels, labeling unlabeled markers, and filling gaps in trajectories. Gaps were filled using a "Pattern Fill". In this feature, a nearby marker, which maintains a constant pattern with respect to the marker with the gap, is used as a reference for filling the gap. When possible, the same reference markers were used to fill gaps of missing markers throughout all trials cleaned across subjects.

The HBM skeletal model was loaded and aided the labeling process. After data cleaning, the Functional Skelton Calibration pipeline was run to calculate joint centers and joint angles. This runs two algorithms. First, it optimizes the skeleton segment and marker parameters [29]. This entails trying to match the skeleton markers from the model to the reconstructed and labeled markers. It does so by changing joint angles, segment poses, and marker positions. Joint types throughout the model constrain motion that is allowed between segments. Second, it calculates joint and marker statistics which assists labeling algorithms. Subject 3 Dynamic Squat and Subject 4 Static Squat had obstructed markers, which prevented the use of this pipeline. Kinematic Fit was run on those in order to calculate joint centers and joint angles [30]. The method serves the same purpose of fitting the skeleton to the marker data, but incorporates weightings to uncalibrated

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values and a mean pose ratio. The effect of using two different kinematic fitting operations is considered apparent in the Chapter 9, Results, and is further examined in Chapter 10, Discussion.

Joint angles were then available for viewing using the graph feature in Nexus. Values were checked to ensure they were reasonable. An image of the Nexus window is provided as Figure 29. It shows the cleaned/labeled markers with the functional skeletal model applied. The left knee joint center is selected and the graph of joint angles over time is provided as well.
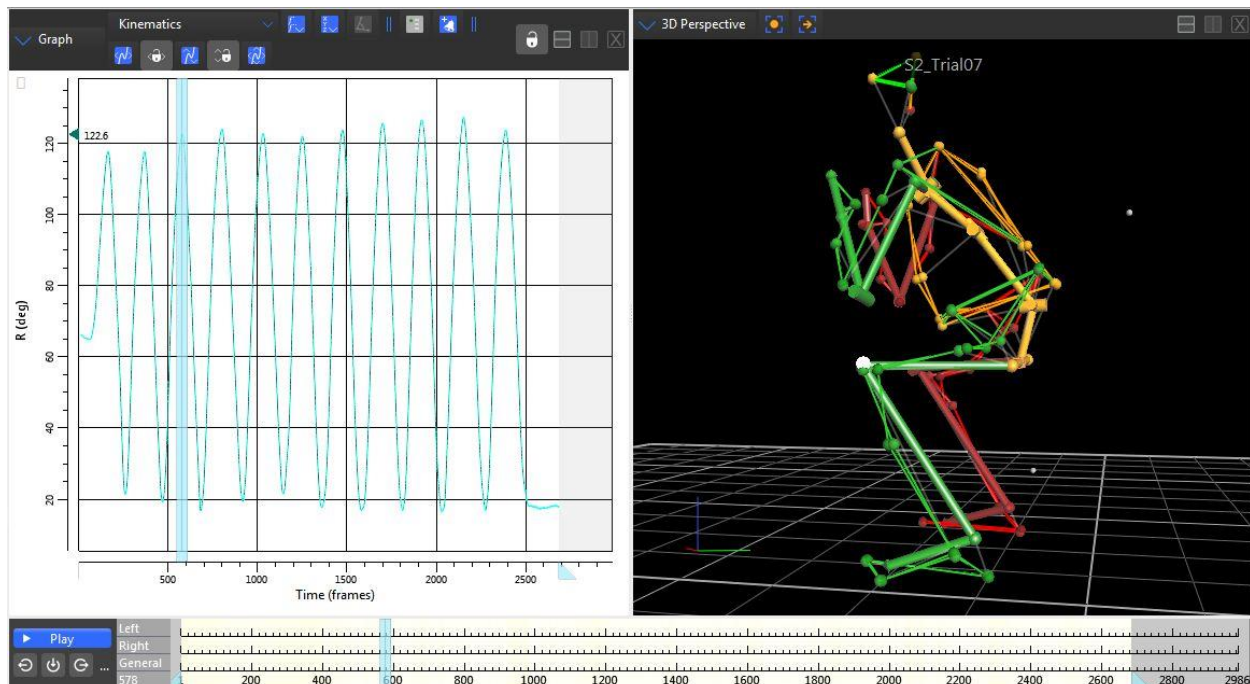
Figure 29: Screen Capture of Nexus During Kinematic Data Processing. Relative Joint Angle from the Tibia to Femur (Left) and Functional Skeleton Showing Joints and Segments (Right).

Joint angles were then exported to a text file for additional processing and plotting in MATLAB.

Only the knee angle ("femur_tibia") for the left and right knee were included in further analysis.

It was considered the primary indicator of exercise completion based on the joint angles available.

8.2.2 Definitions and Computations

Nexus provided the relative knee joint angle as an external angle from the tibia to the femur.

An inner knee angle was of interest though so angles were subtracted from 180 degrees, as shown in Figure 30.

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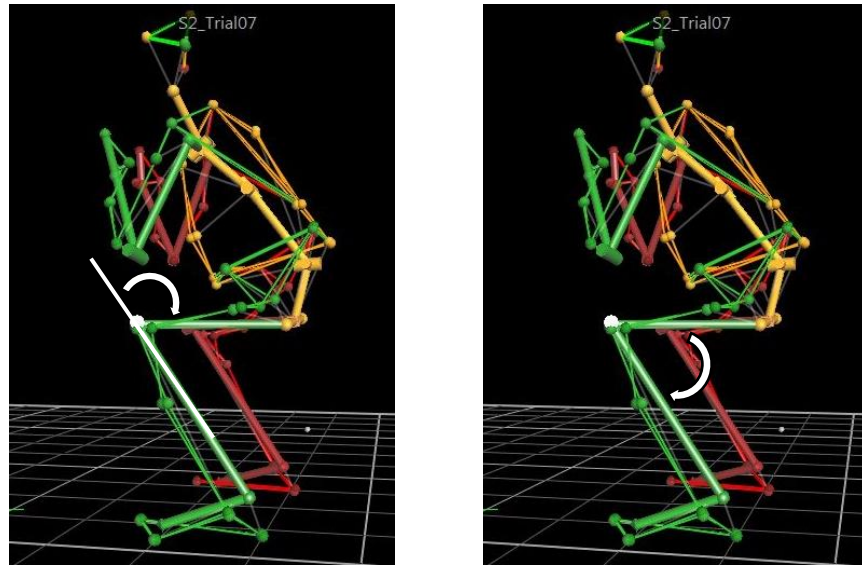
(a) Nexus Definition   (b) Definition in This Study

Figure 30: Relative Knee Angle Definitions

The Range of Motion (ROM) of Knee Angle during exercise, as it applies to this study, is defined as the difference between the minimum knee angle and the maximum knee angle in each individual cycle of exercise (repetition). For all intents and purposes in this thesis, knee flexion refers to the eccentric motion of the leg (bending knee) and knee extension refers to the concentric motion of the leg (straightening knee). A similar process to the Kinetic analysis was followed to find the peaks and troughs associated with each exercise cycle. Then, Knee ROM was found for each cycle. These values were then averaged to find the Knee ROM presented in the Results. In order to position this averaged ROM within the appropriate angles, and average midpoint was found using the average of the peaks and troughs for each cycle. The Knee ROM data were then centered on these midpoints. The corresponding MATLAB script is included in the Appendix F.

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8.3 Description of Results Presentation

8.3.1 Kinetic Results Presentation

In order to visualize frequency matching, the following was performed for the combined Force and Platform motion plots throughout the Kinetic Outcomes sections in Chapter 9, Results. Figure 31 provides an example of this process.

1. Using the event counter in the saved data (increments of "Activate Motion" and "Stop Motion"), Force data and Platform data were parsed to the start and stop points of the platform motion. Note that both Force and Platform data were recorded at the same frequency and shared the same array lengths (i.e., they start and end at the same time), so using the event counter was not needed for synchronicity (though it ensured it) but rather for parsing data to the region of interest.

2. The resultant force profiles in the Y direction and the sinusoidal platform motion, also in Y, were normalized to maxima so that both could be displayed on the same graph. To further clarify, the maximum force throughout the cycles in the parsed data was set to one. For the platform motion, maximum (positive) displacement of the actuators was set to one. Also, time (x-axis) was shifted to zero so that trial length was more easily viewed.

3. The sinusoidal platform motion is represented by a gray line, and the force profile by a blue line. To enhance readability of the graphs, and to provide clarity on which part of the cycle forces are being observed, a lighter gray shaded area was added under the sinusoid. The gray area represents increasing-decreasing platform displacement, and the white area represents decreasing-increasing displacement.

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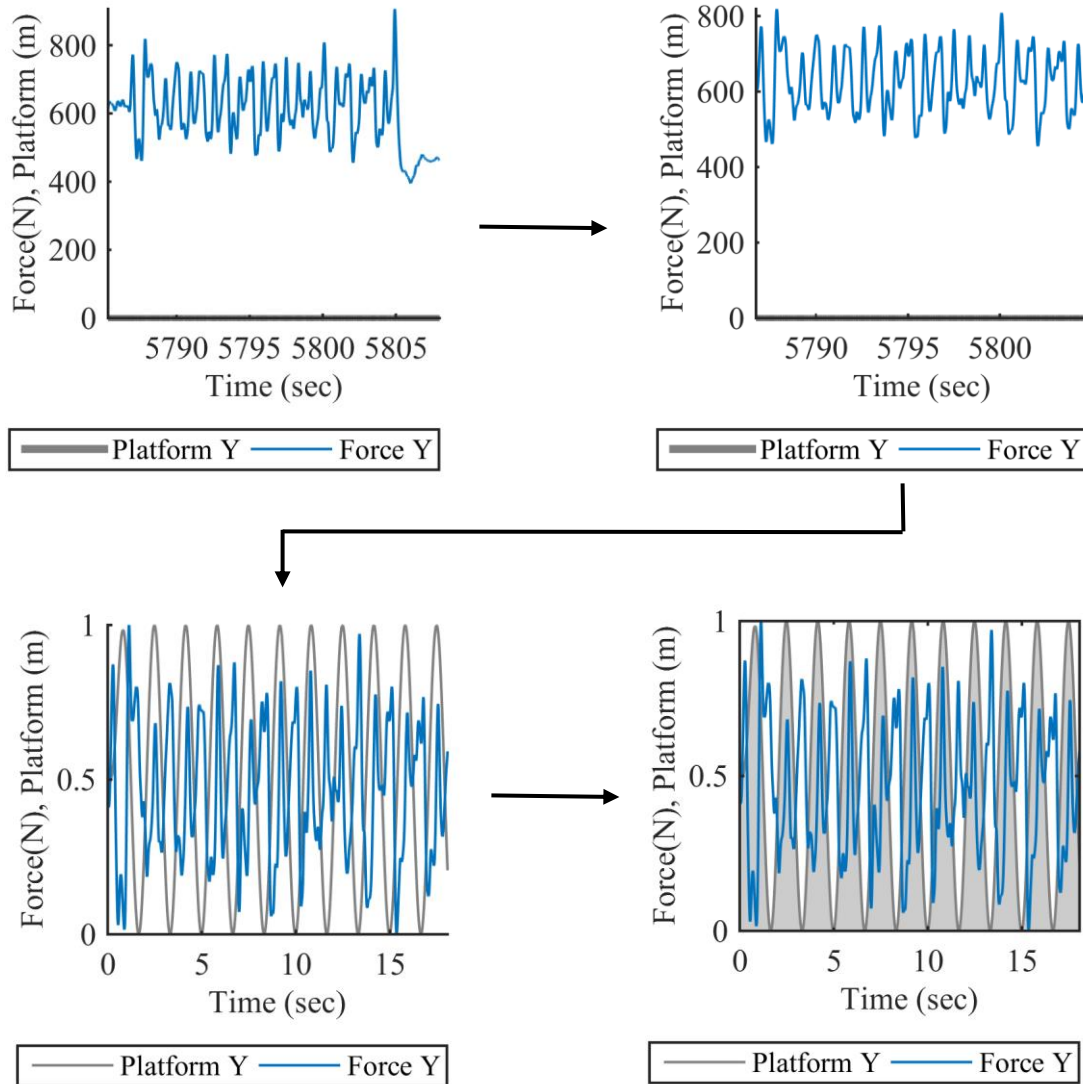
Figure 31: Process for Obtaining Kinetic Outcome Result Graphs. Original Filtered Force and Platform Data (Top Left), Parsed Data (Top Right), Normalized (Bottom Left), and Normalized + Shaded (Bottom Right).

8.3.2 Kinematic Results Presentation

The graphs in the Kinematic Results sections provide the knee change in angle over time for at least 6 exercise cycles for each subject. Each graph begins at the first peak available in the data. Note that 1-3 squats may have preceded the first peak in the data. The graphs are shared to provide a visual aid for observing what level of consistency across cycles was achieved and how

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that varies from Static to Dynamic. One can also study the frequency of exercise on the graphs. Ideally, each should match the baseline measurement.

The Knee Angle ROM is presented for all subjects in a combined bar graph which compares the Static and Dynamic conditions. Angles from the left and right knees were provided as calculated from the Nexus models. Figure 32 provides an example overlay showing the skeletal model from which joint angles were calculated and a screenshot of the video from the associated trial. Note that Figure 32 was created through video editing and any positional offsets observed are not necessarily representative of the alignment of the model with motion capture markers. The perspective views are offset and the overlaid images may be from slightly different frames in the recordings. Nexus provides a better overlay capability when integrated video cameras are used.
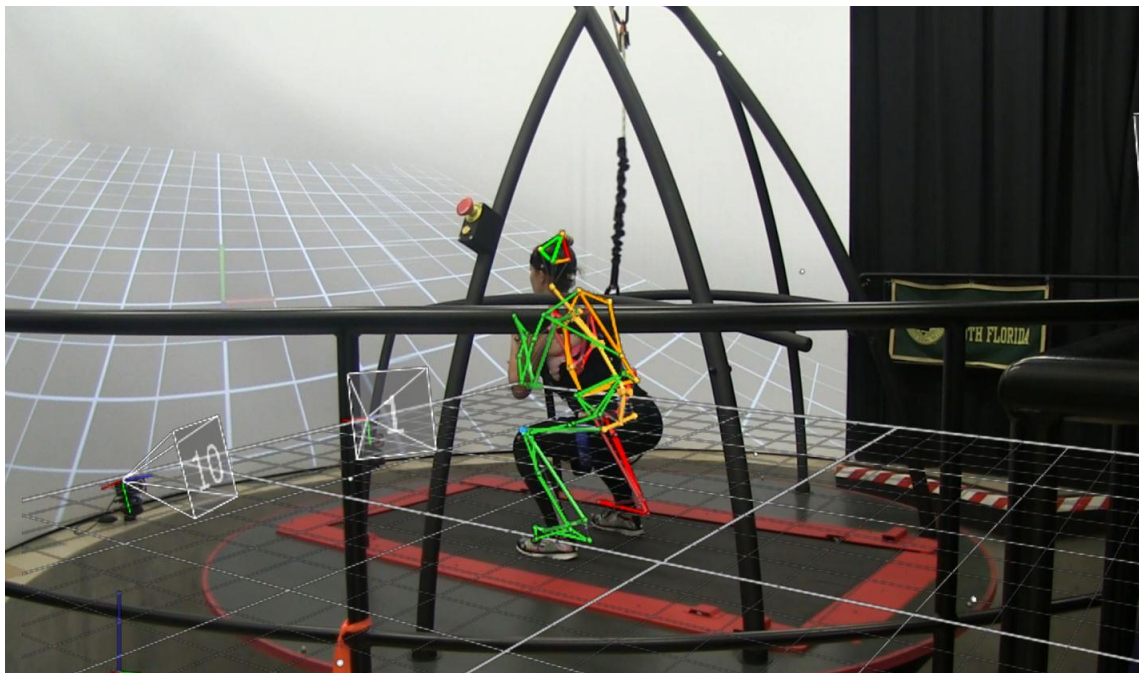
Figure 32: Example Overlay of Functional Skeleton Model on Video Image from Same Squat Trial

CHAPTER 9: RESULTS

9.1 Subject Parameters

As mentioned in Chapter 7, Experimental Design Implementation, subject attributes were recorded and baseline amplitude and frequencies for use in the Experimental Trials were measured. These parameters are shared in Tables 14 and 15 and are of value to reference throughout observation of results.

Table 14: Subject Attributes

Subject Designation	Gender	Age	Height (ft / m)	Weight (lbs / N)
S1	Female	18	5.68 / 1.73	136.0 / 605.0
S2	Female	22	5.31 / 1.62	121.2 / 539.1
S3	Female	44	5.25 / 1.60	148.2 / 659.2
S4	Male	22	6.10 / 1.86	172.2 / 766.0

All subjects were in-between astronaut historical heights of 4' 10" (1.47 m) and 6' 2" (1.88 m).

Table 15: Subject Specific Baseline Measurements. Each Used As Baseline Amplitude and Frequency Inputs to Platform Motion

	Baseline Measurements		
Subject	Amplitude (m)	Frequency of Squats (Hz)	Frequency of Rowing (Hz)
1	0.0470	0.4167	0.4068
2	0.0355	0.4460	0.5750
3	0.0385	0.4916	0.5061
4	0.0475	0.6711	0.5695

With the exception of Subject 4 Squats, all subjects had comfortable, baseline exercise frequencies between the 0.35 Hz and 0.60 Hz fixed frequencies tested in this study.

9.2 Squats

9.2.1 Kinetic Outcomes

9.2.1.1 Ground Reaction Forces

The following graphs provide the Static, unperturbed baseline and the Dynamic baseline Ground Reaction Force (in the Y component) for each subject in the Squat exercise. Lowest troughs correspond to reaching a full squat and highest peaks correspond to standing. The first 1-2 seconds represents a period where the subject was standing relatively still.

It can be observed that the force profile changes between the Static platform and Dynamic platform condition, where the subject is exercising at their baseline frequency. One of the most notable differences is the increased force attributed to the secondary peaks, which occurs as a complete squat is reached.
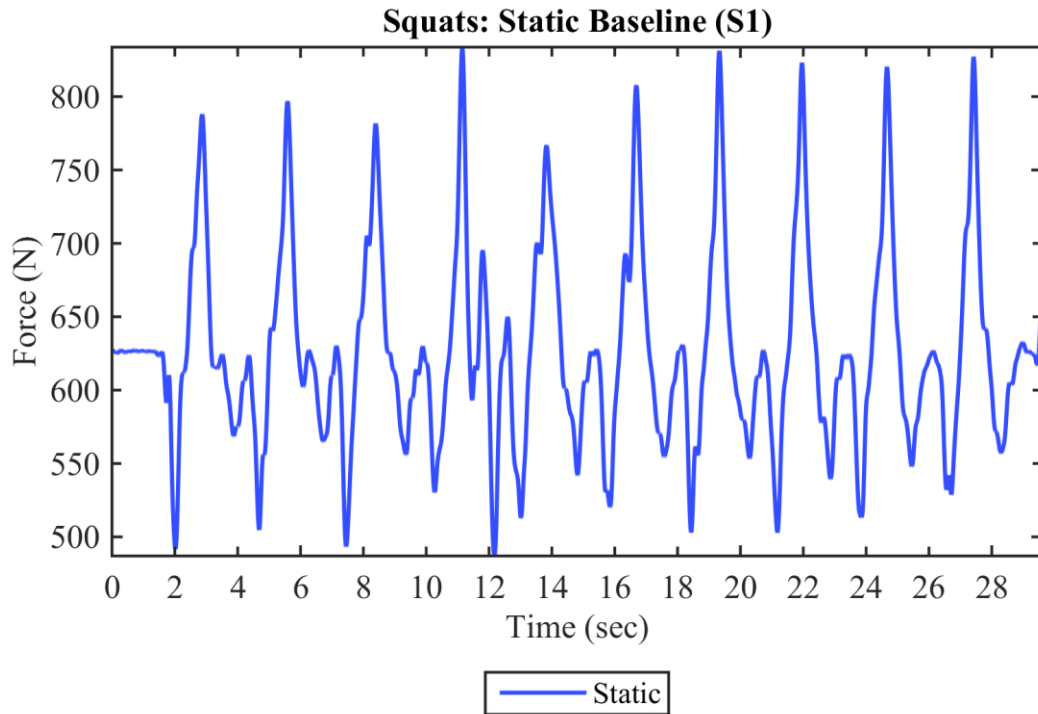
Figure 33: Filtered Resultant Force Data of Static Baseline Squat for Subject 1
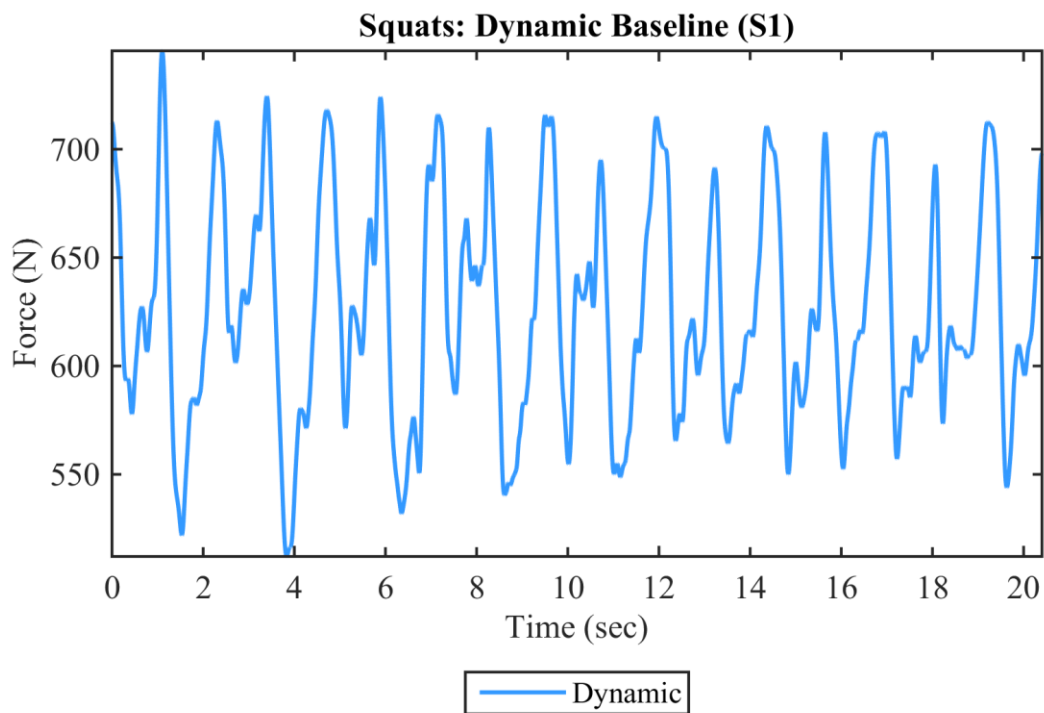
Figure 34: Filtered Resultant Force Data of Dynamic Baseline Squat for Subject 1

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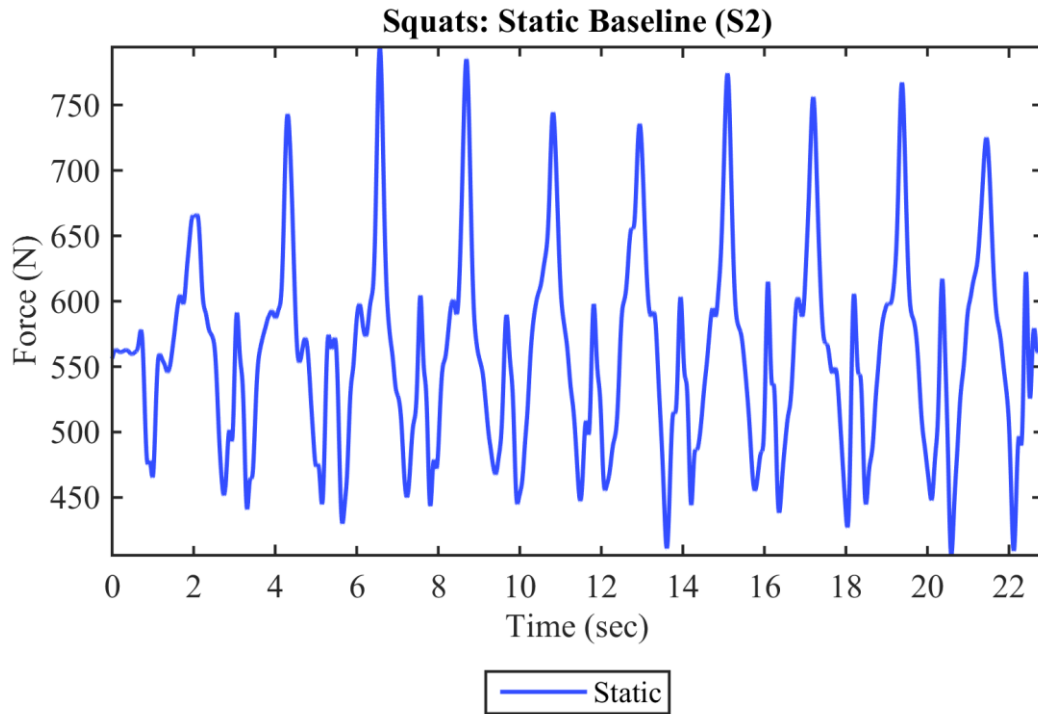
Figure 35: Filtered Resultant Force Data of Static Baseline Squat for Subject 2
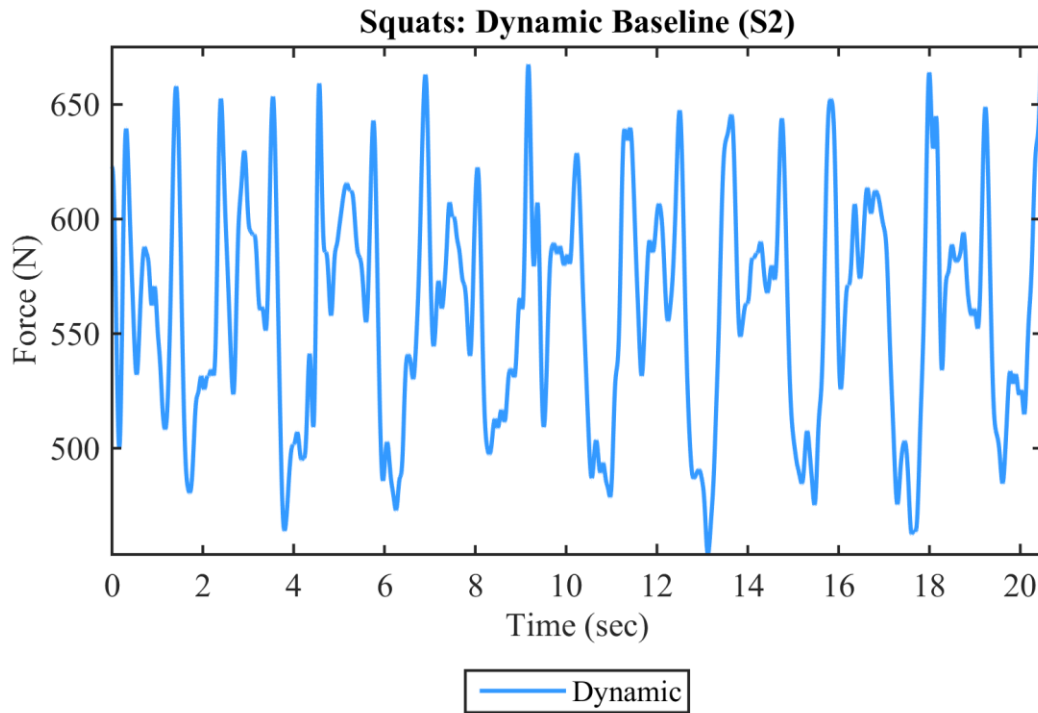
Figure 36: Filtered Resultant Force Data of Dynamic Baseline Squat for Subject 2
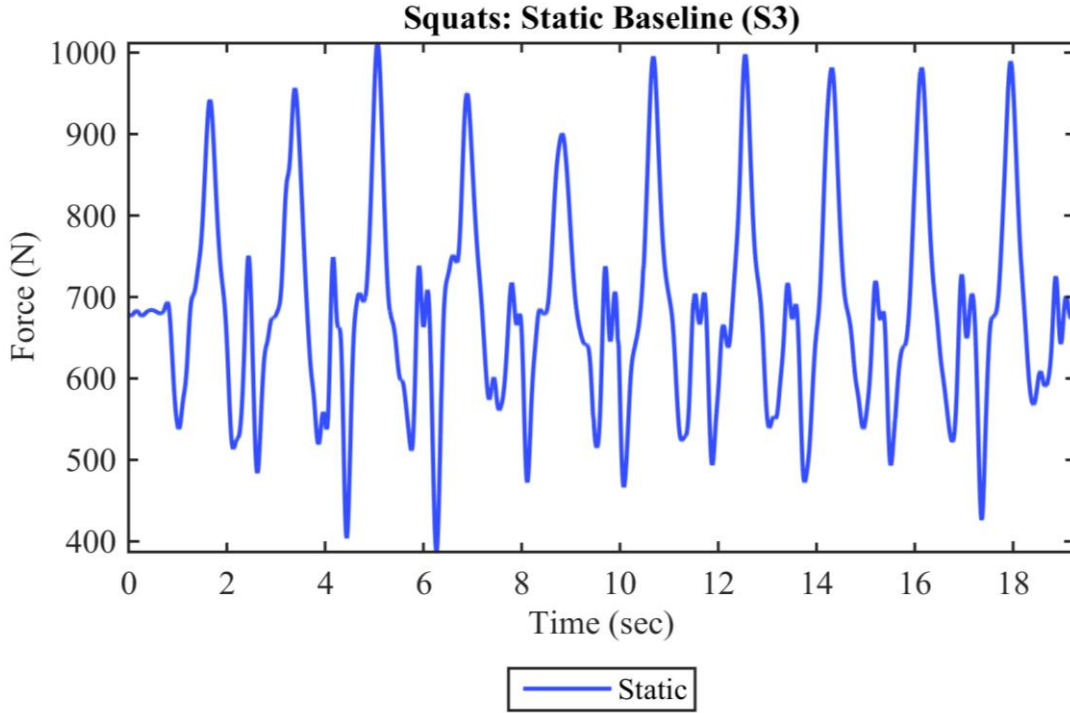
Figure 37: Filtered Resultant Force Data of Static Baseline Squat for Subject 3
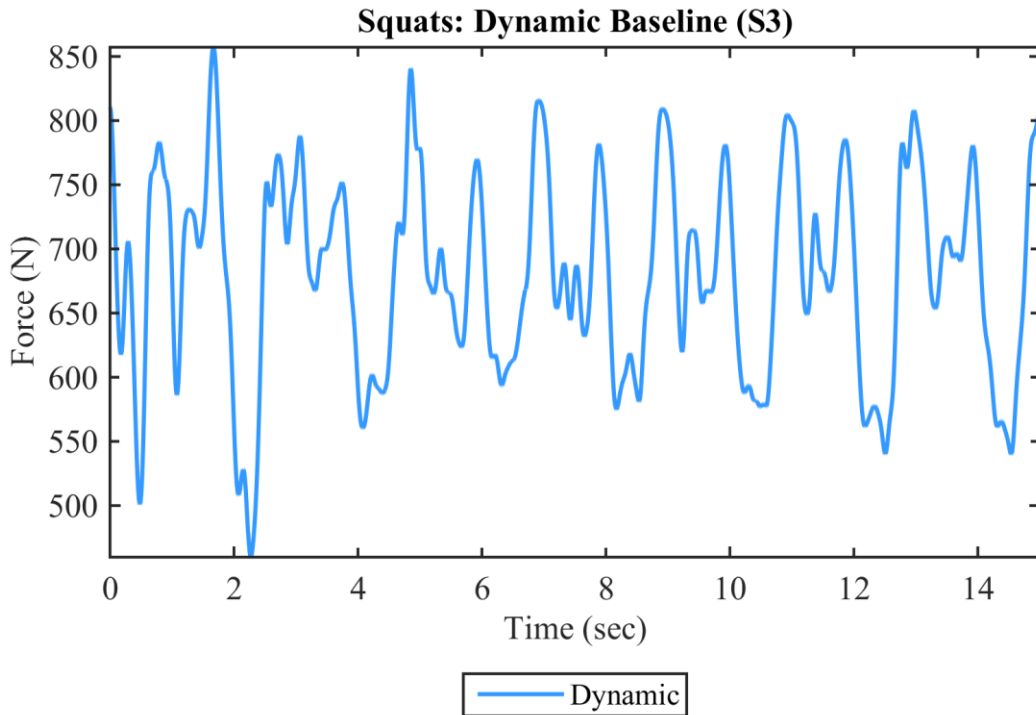
Figure 38: Filtered Resultant Force Data of Dynamic Baseline Squat for Subject 3

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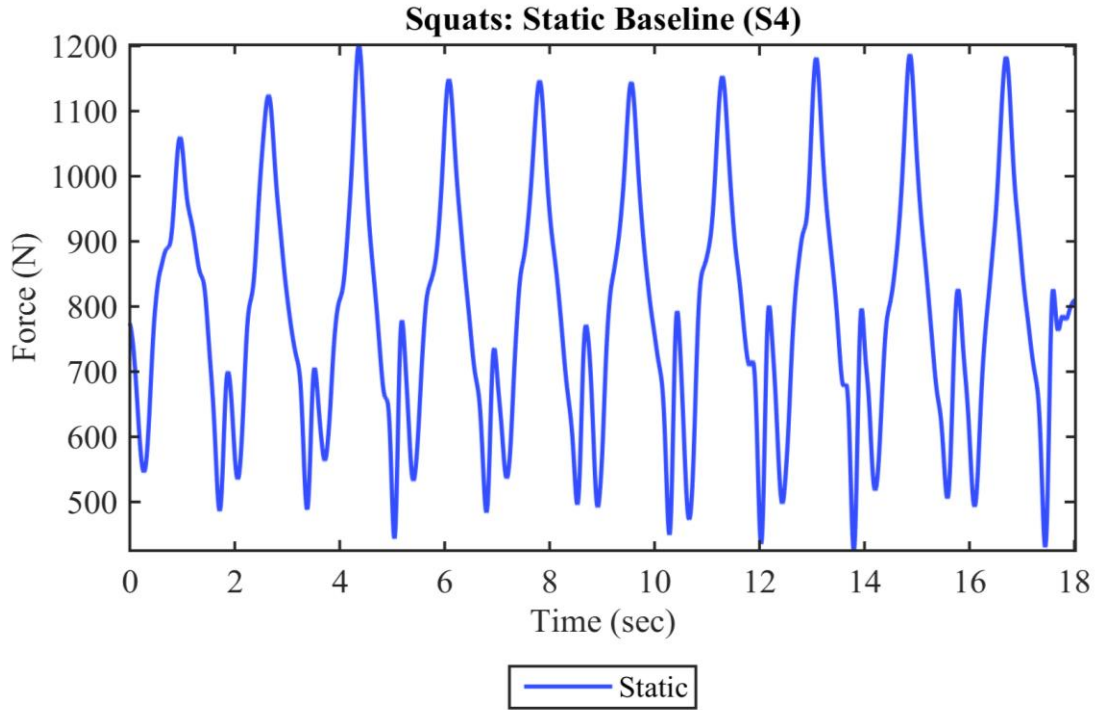
Figure 39: Filtered Resultant Force Data of Static Baseline Squat for Subject 4
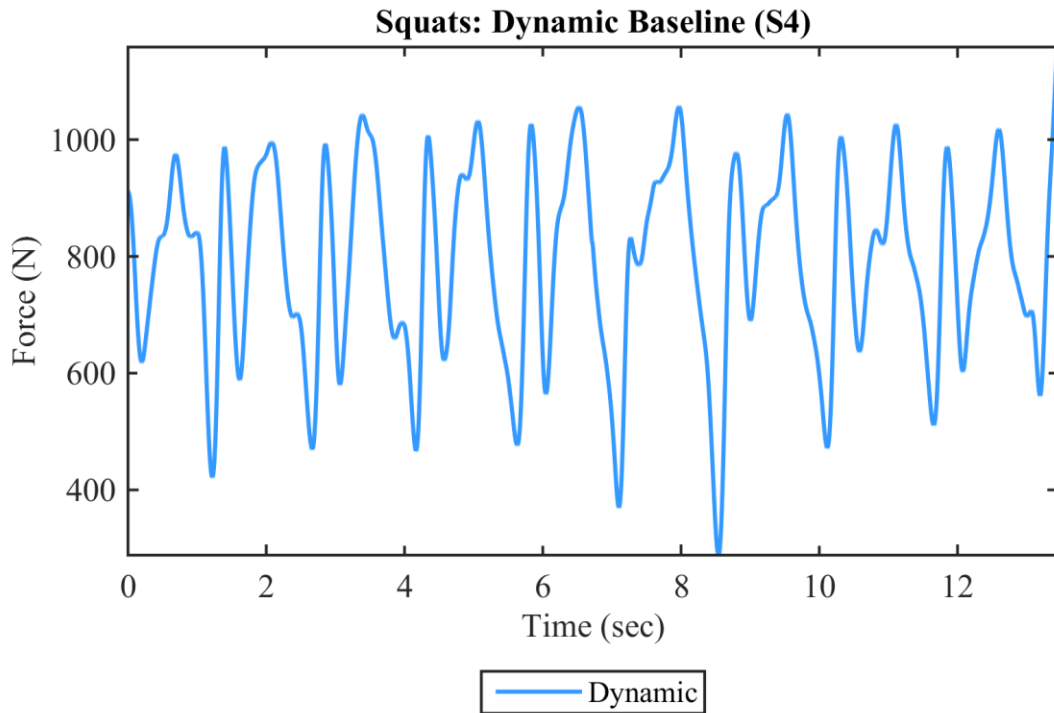
Figure 40: Filtered Resultant Force Data of Dynamic Baseline Squat for Subject 4

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9.2.1.2 Maximum Forces and Force Ranges

Figure 41 shows the average maximum forces and Figure 42 shows the average force range, both corresponding to the Y component of ground reaction force. For Subjects 1-3, the same relationships between test conditions were seen. The average maximum force and average maximum range increase with frequency. The Dynamic baseline condition exhibits lower maximum forces and ranges. This Dynamic baseline also has lower forces than the 0.60 Hz frequency, which is expected given those subjects had baseline frequencies lower than 0.60 Hz. For Subject 4, it is reasonable that the Dynamic baseline is higher than the 0.60 Hz condition, given that the subject has a baseline squat frequency above 0.60 Hz. However, it is unusual that the Dynamic baseline condition resulted in higher forces than the Static baseline condition for Subject 4, unlike other subjects. The 0.35 Hz condition was also greater than the Static baseline for this subject, which was not the case for other subjects.
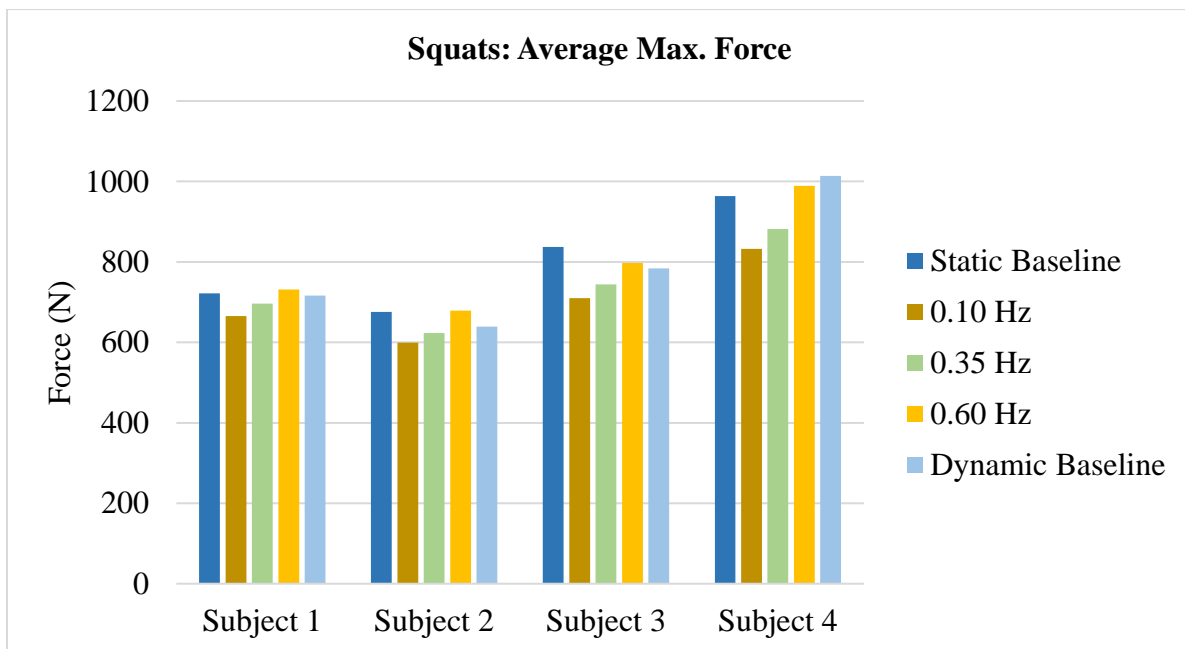
Figure 41: Average of Maximum Force Across All Cycles in a Trial for Squats
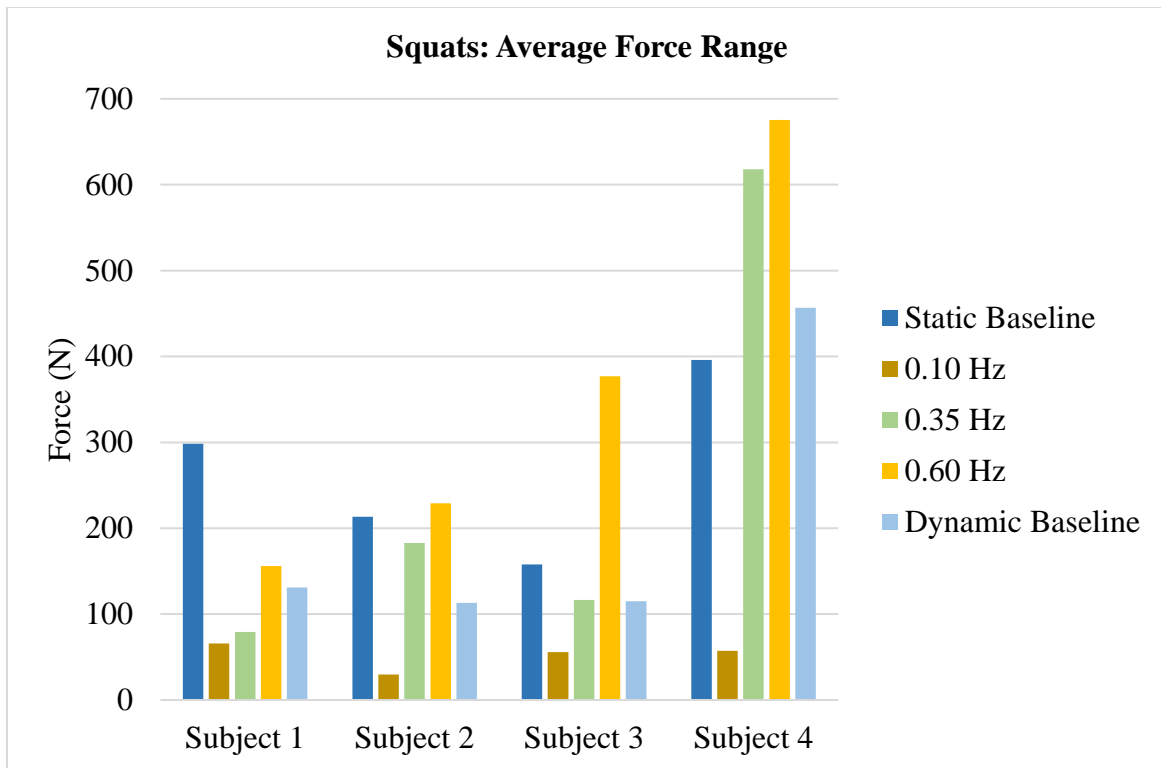
Figure 42: Average of Range of Forces Across All Cycles in a Trial for Squats

9.2.1.3 Force Frequency Matching

The following graphs provide visualization of each subject's ability to match the frequency of the platform motion. In the ideal case, the maxima would align.
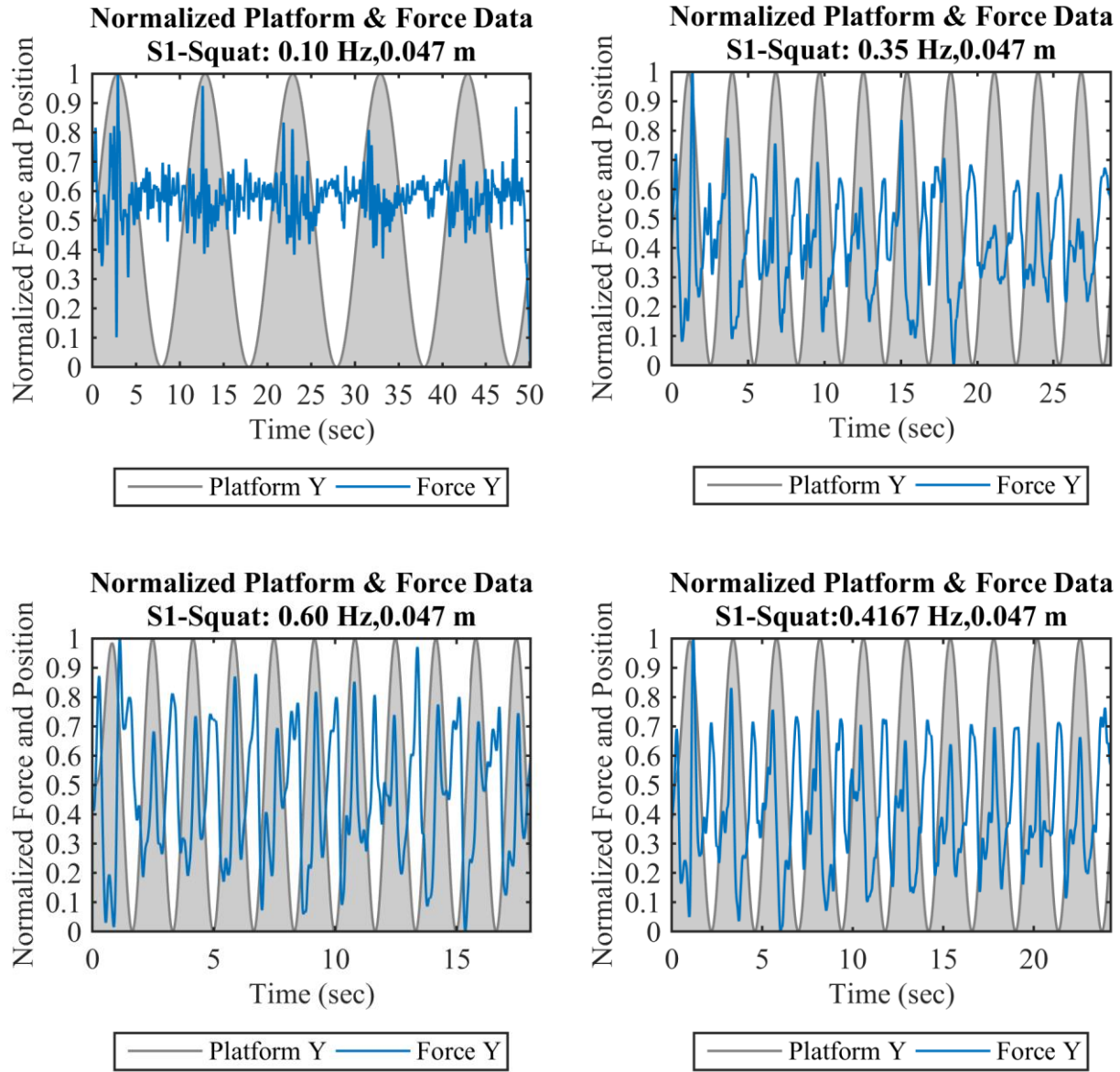
Figure 43: Synchronized and Normalized Force & Platform Squat Data for Subject 1
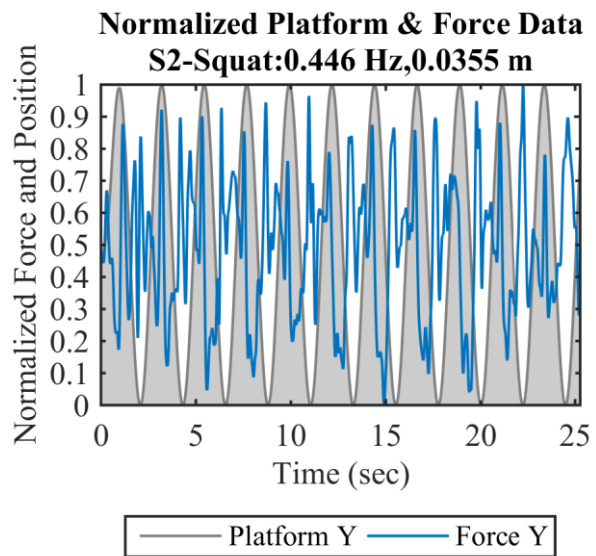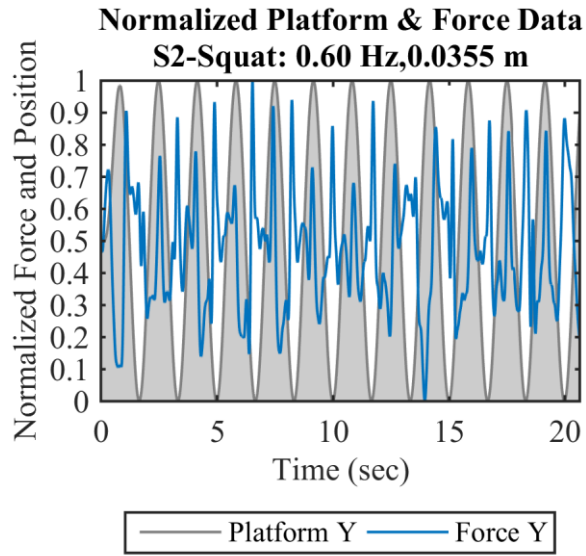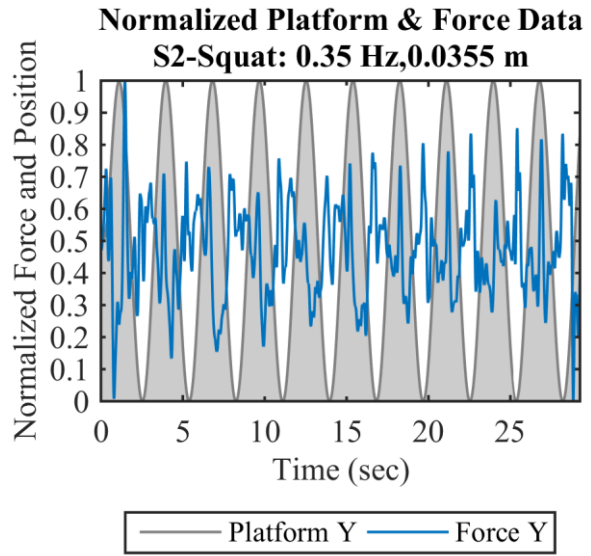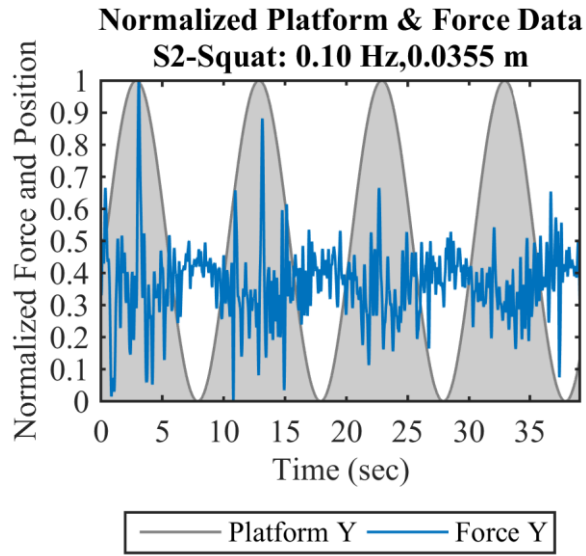
Figure 44: Synchronized and Normalized Force & Platform Squat Data for Subject 2
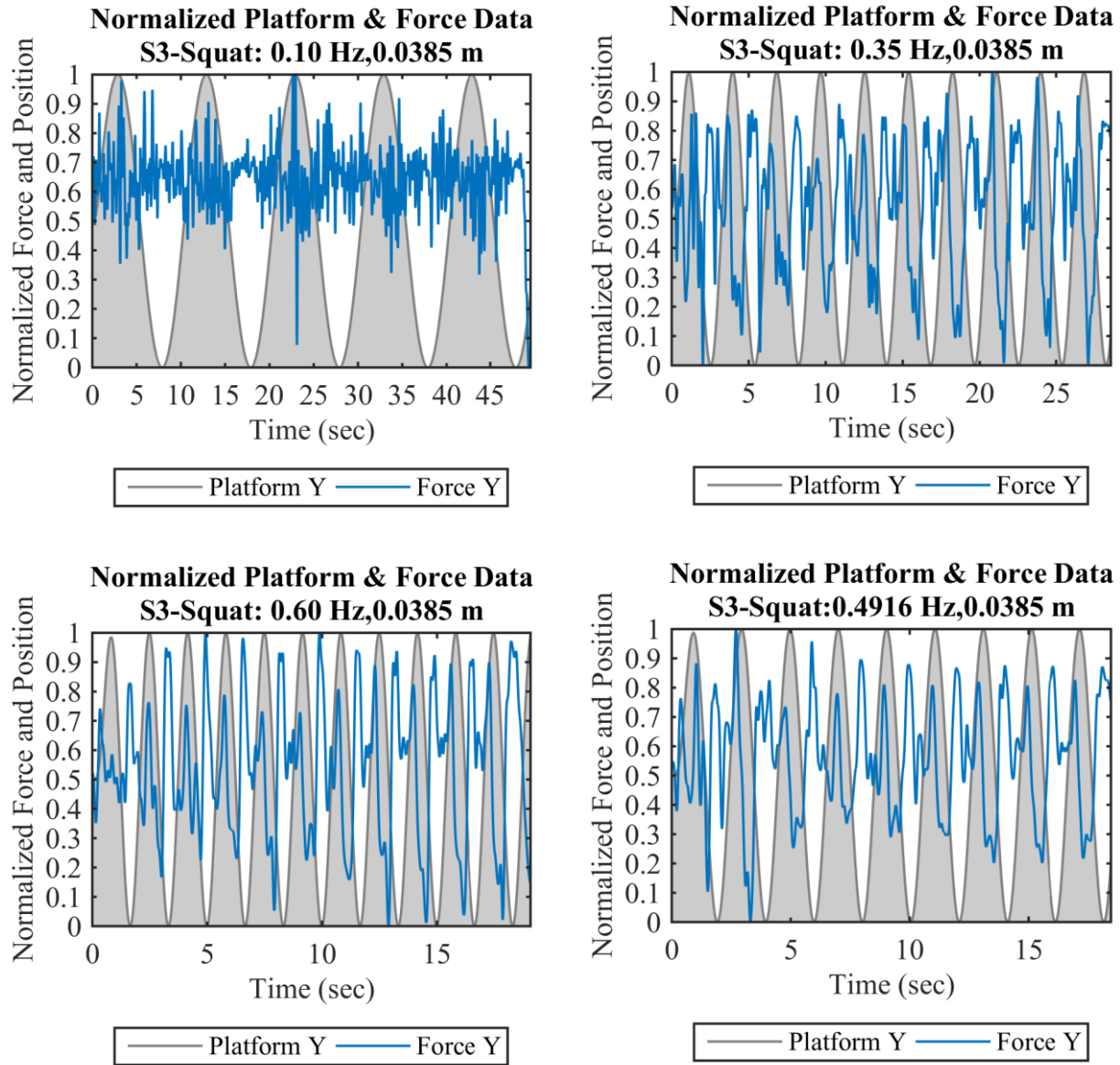
Figure 45: Synchronized and Normalized Force & Platform Squat Data for Subject 3

The Dynamic Baseline Squat for Subject 3 (bottom right plot of Figure 45) provides one of the more synchronized trials. Notice the alignment of primary peaks, associated with the subject standing, with the platform lowest displacement. The secondary peaks are primarily left justified to the gray shaded area, showing that the subject performed the squat down motion as the platform was displacing upward. The smaller amplitude of these secondary peaks is also representative of squatting down in the correct time with the platform movement.
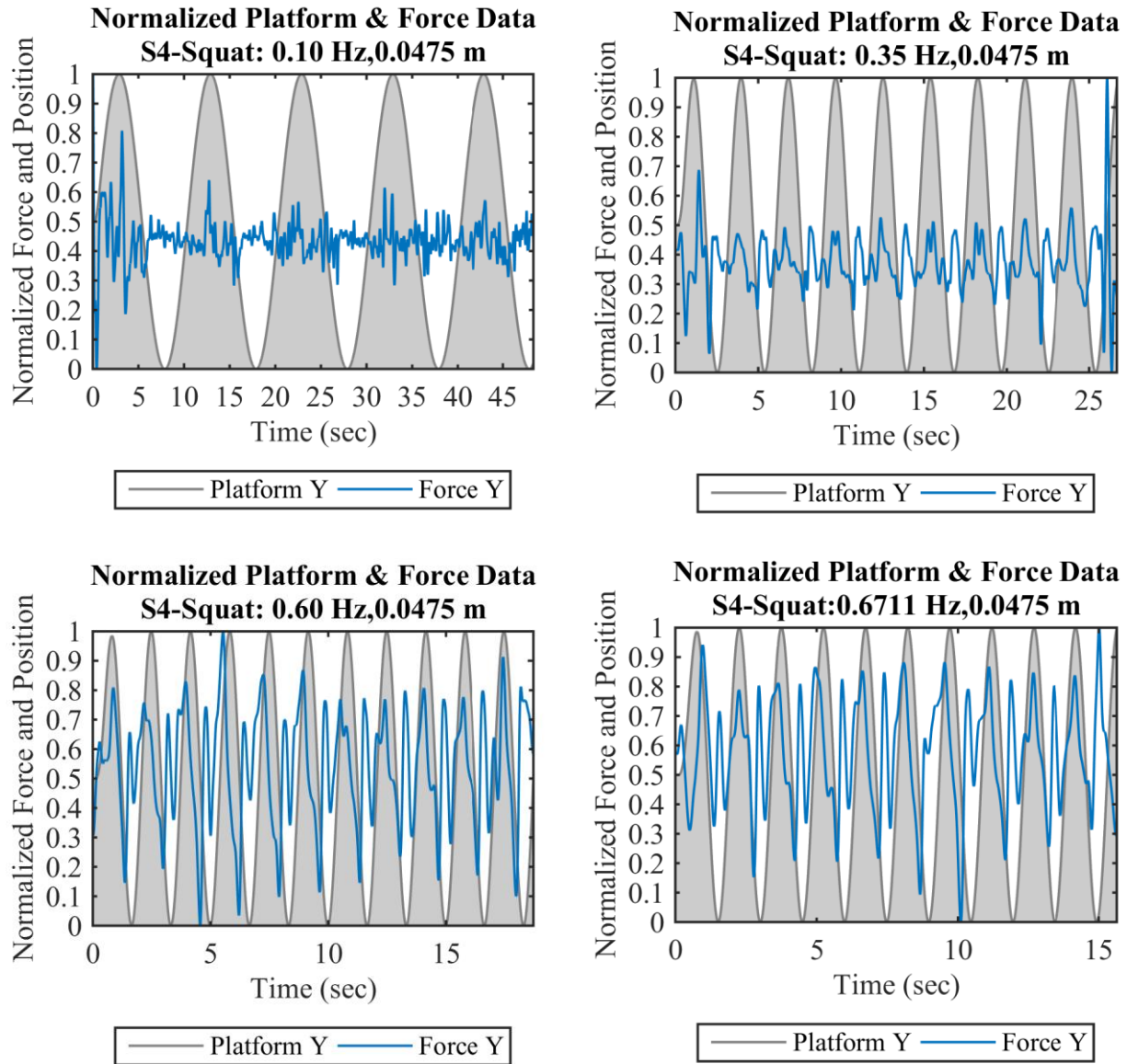
Figure 46: Synchronized and Normalized Force & Platform Squat Data for Subject 4

The Dynamic Baseline Squat for Subject 4 (bottom right plot of Figure 46) shows one of the more unsynchronized trials. The force profile around 8 seconds is of most interest, showing the result of being out of phase from the target synchronization.

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9.2.2 Kinematic Outcomes

9.2.2.1 Knee Angle Trajectories

For the Knee Angle Trajectories, the left and right knee angles are shown on separate graphs and the intention is to compare the exercise on the Static platform versus Dynamic platform for the baseline conditions. A squat repetition was completed between each peak (each trough represents knees bent).

Subject 1, Figure 47, had relatively consistent flexion across all cycles, with total knee ROM being smaller in the Dynamic case. Static Baseline was lower in frequency. Subject 2, Figure 48, had relatively consistent flexion and extension across all cycles, though Dynamic had some cycles with lower amplitude. Static Baseline was a slightly higher frequency. Subject 2 also had a slight increase in amplitude (knee angle range) over the first couple of repetitions in the Dynamic condition, possibly related to acclimation. Subject 3, Figure 49, had more consistent cycles on Static than in the Dynamic case. Static Baseline was a higher frequency. Subject 4, Figure 50, had relatively consistent flexion and extension across all cycles. Static Baseline was a slightly slower frequency.
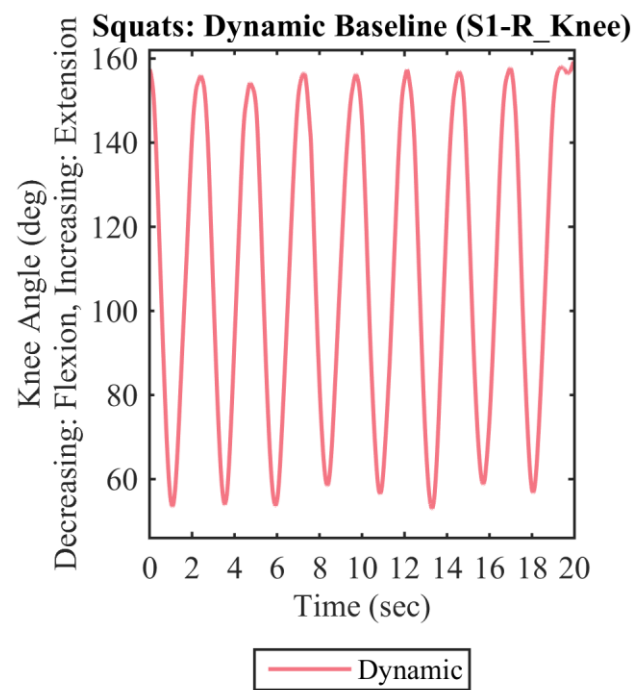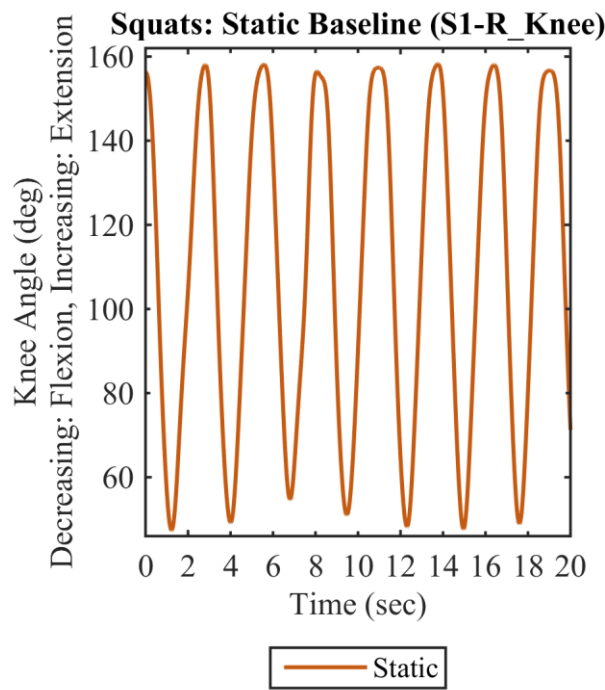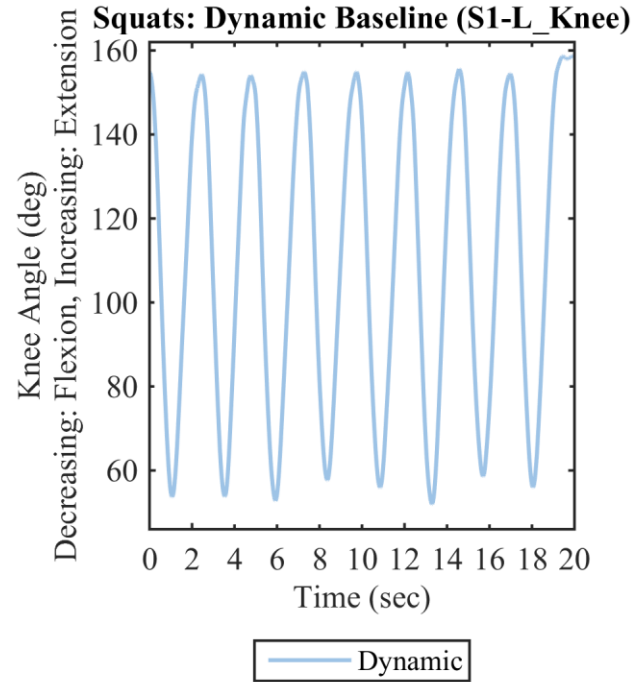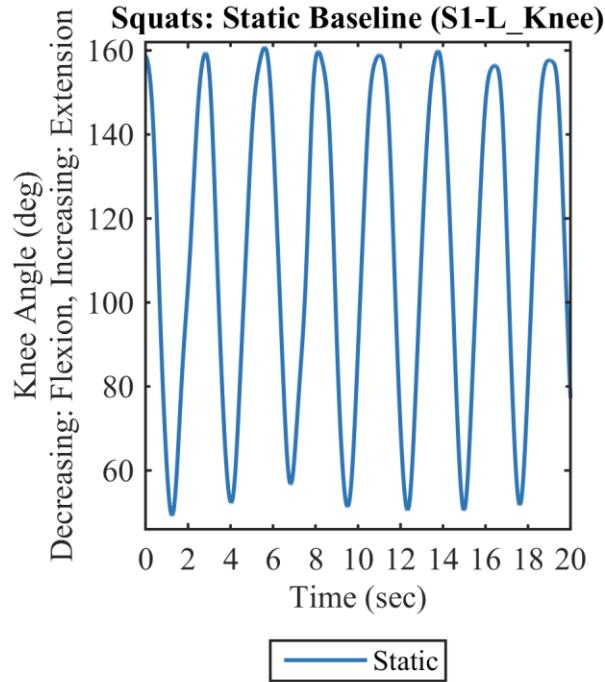
Figure 47: Subject 1 Baseline Frequency Squats with Static Platform (Left) and Dynamic
Platform (Right). Left Knee Angle (Top) and Right Knee Angle (Bottom).
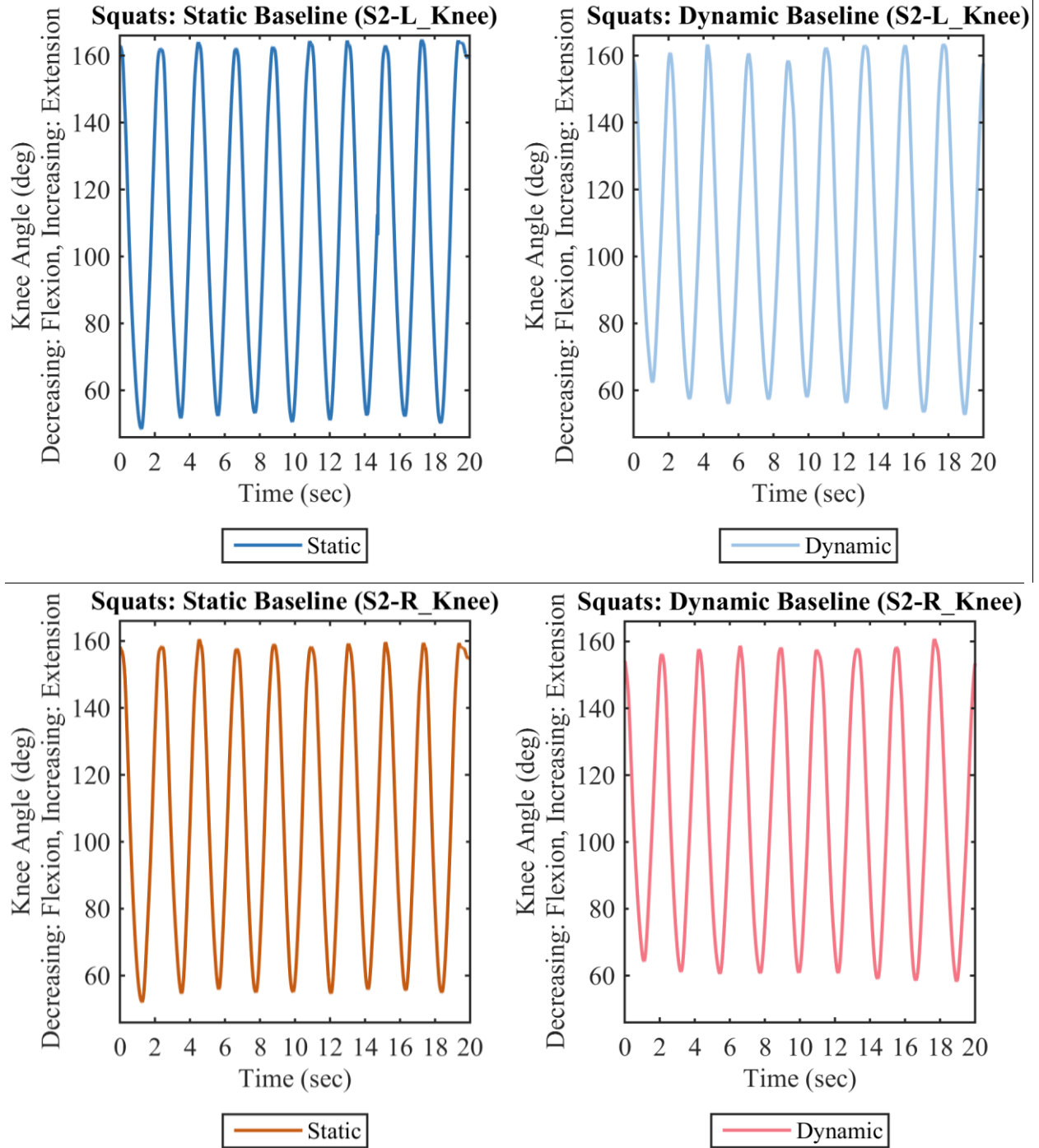
Figure 48: Subject 2 Baseline Frequency Squats with Static Platform (Left) and Dynamic Platform (Right). Left Knee Angle (Top) and Right Knee Angle (Bottom).

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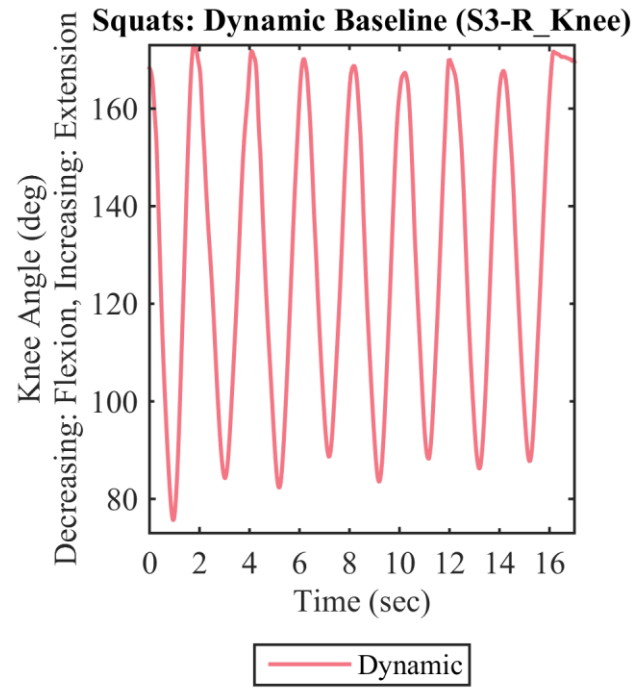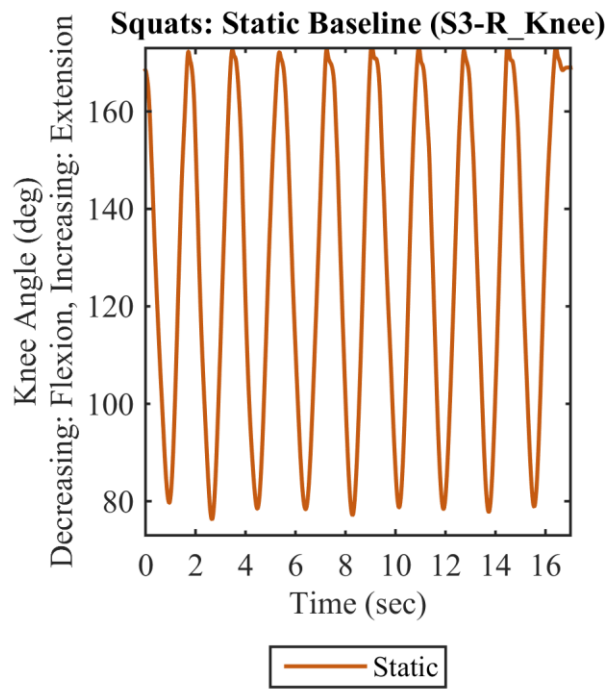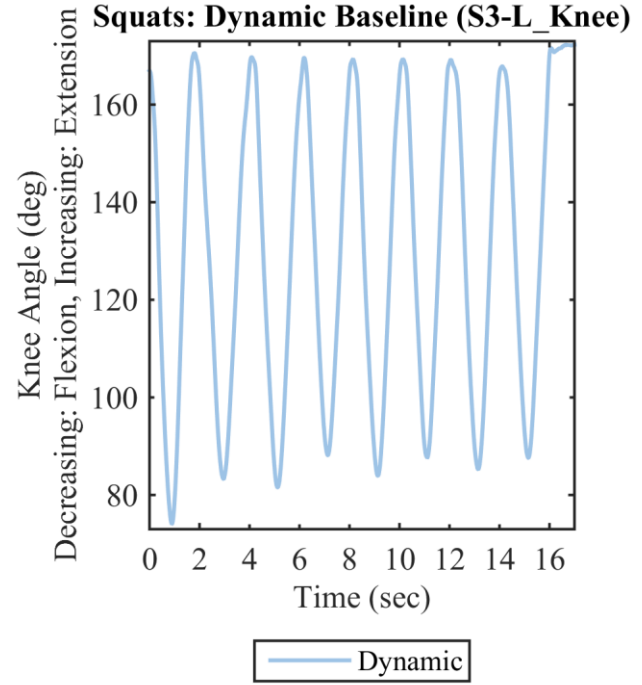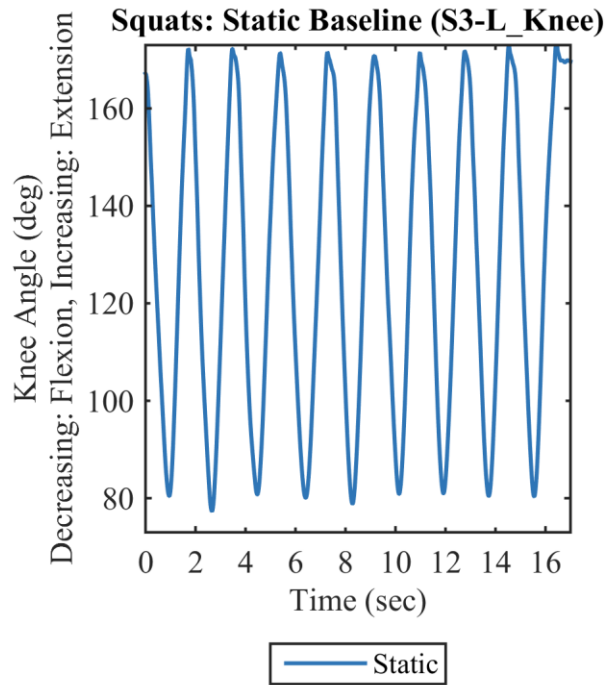
Figure 49: Subject 3 Baseline Frequency Squats with Static Platform (Left) and Dynamic Platform (Right). Left Knee Angle (Top) and Right Knee Angle (Bottom).

Figure 50: Subject 4 Baseline Frequency Squats with Static Platform (Left) and Dynamic Platform (Right). Left Knee Angle (Top) and Right Knee Angle (Bottom).

9.2.2.2 Knee Angle Range of Motion

The results for Knee Angle ROM for left and right knee during Static and Dynamic Squats are presented in Figure 51.
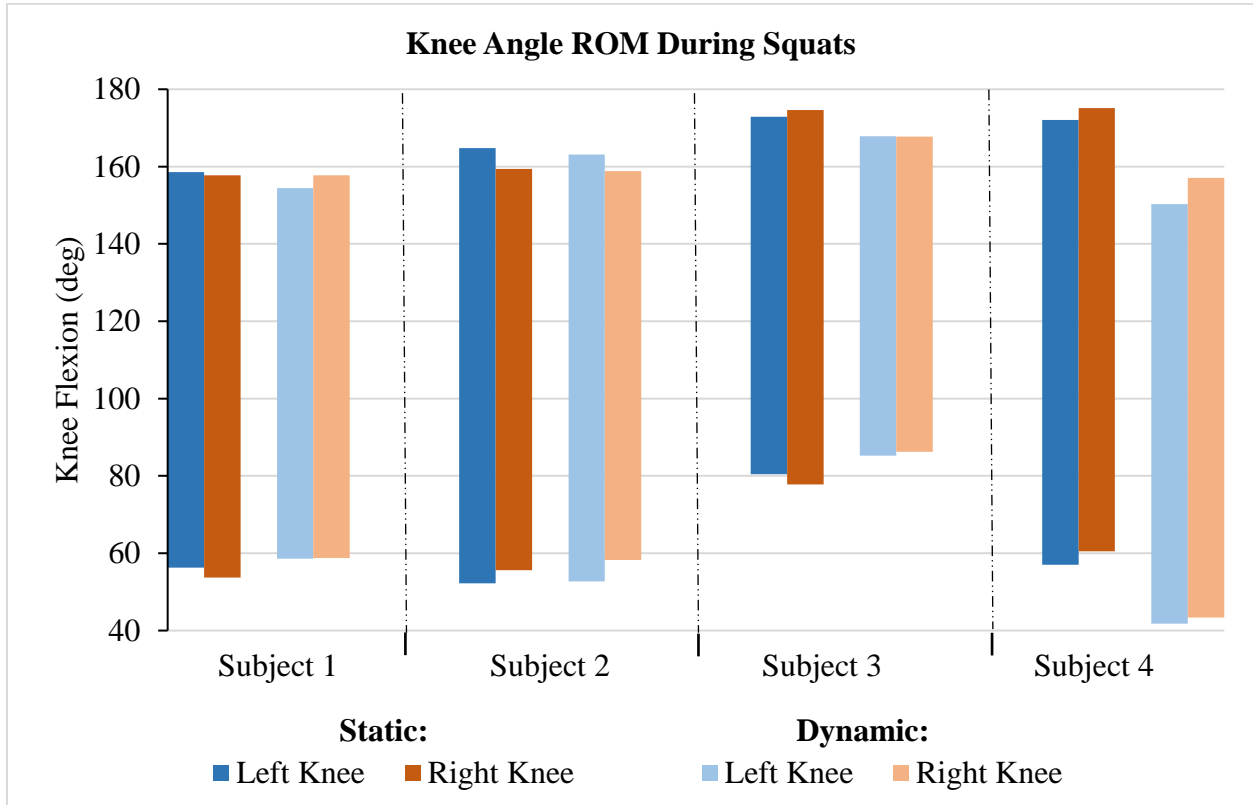
Figure 51: Average Range of Motion Across Exercise Cycles of Inner Knee Angle, Comparing the Static to Dynamic Platform During Squats

Results show that knee angle range of motion was similar between the left knee Static and left knee Dynamic baseline conditions; the same applies to the right knee. The total range of motion was near the 90° instructed during training. The minimum Knee ROM was ~82° (Subject 3 Dynamic Baseline) and maximum Knee ROM was ~115° (Subject 4 Static Baseline). For Subject 3, the Knee ROM decreases between Static and Dynamic conditions more so than the other subjects. The midpoint of Knee ROM shifts downward for Subject 4, which is addressed further in Chapter 10, Discussion.

9.2.3 Questionnaire Responses

Four questions on the questionnaire pertained specifically to squats, as described in 7.3.5 Questionnaire. Each subject's ratings are presented in Table 16. Additional explanation is provided in Appendix C.

Table 16: Questionnaire Results Specific to the Squat Exercises

Question	Subject Designation			
	S1	**S2**	**S3**	**S4**
6	*I was able to complete a squat as instructed while the platform was moving*			
	Agree	Agree	Strongly Agree	Strongly Agree
7	*I found it difficult to complete the squats while the platform was moving*			
	Agree	Disagree	Disagree	Strongly Disagree
8	*I was able to <u>adapt to/match/sync with</u> the platform motion during squats*			
	Neutral	Agree	Neutral	Strongly Agree
9	*I felt that completing the squat exercises while the platform was moving was comfortable*			
	Neutral	Agree	Agree	Strongly Agree

Subject 1 was distinguished from the group in that she considered the squats difficult. However, she felt she was still able to complete the squats. Additional comments were provided and are included in the Appendix C.

9.3 Rowing

9.3.1 Kinetic Outcomes

9.3.1.1 Ground Reaction Forces

The following graphs provide the Static, unperturbed baseline and the Dynamic baseline Ground Reaction Force (in the Y component) for each subject in the Row exercise. Troughs and smaller peaks correspond to the "recover"/"catch" stages of the rowing cycle and the larger peaks correspond to the "finish". Changes to the force profiles can be observed. Just as with the Squat exercise, the Row secondary forces are larger.

81
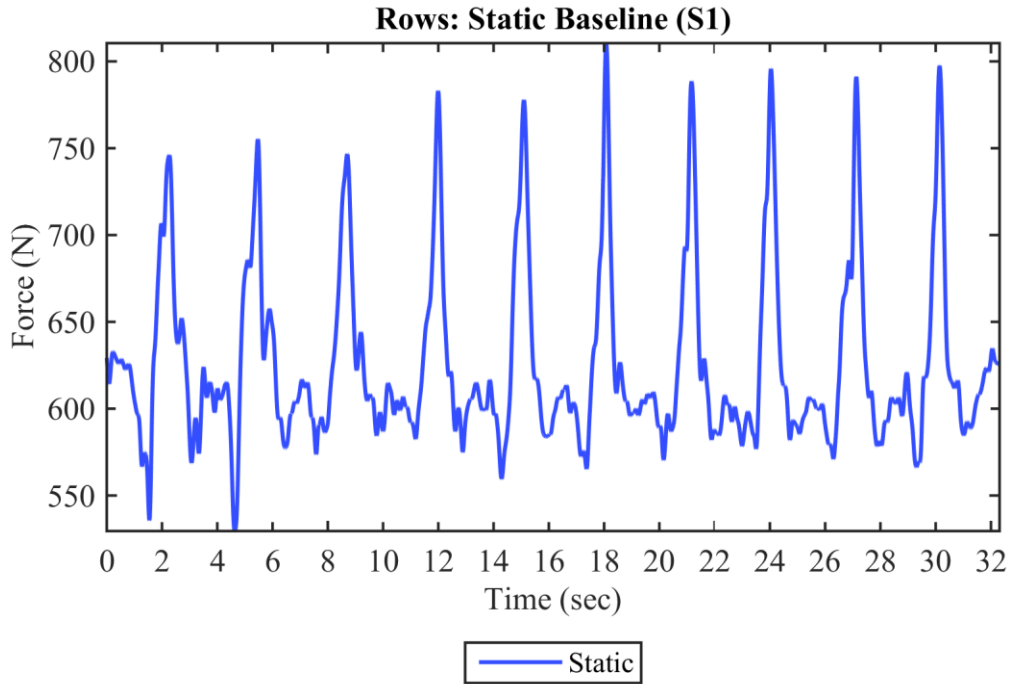
Figure 52: Filtered Resultant Force Data of Static Baseline Row for Subject 1
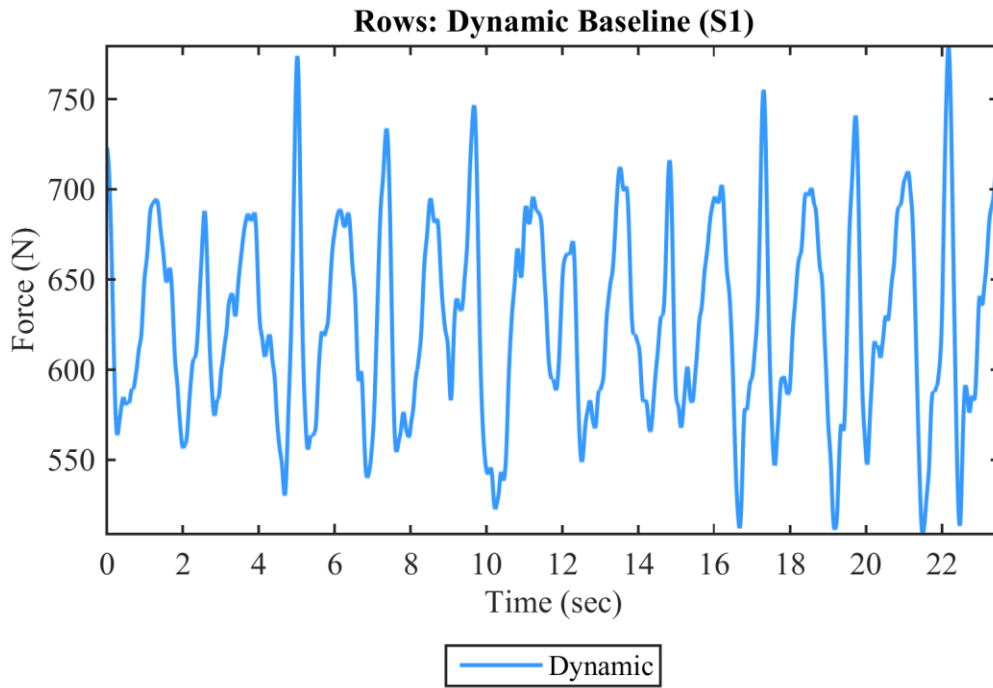
Figure 53: Filtered Resultant Force Data of Dynamic Baseline Row for Subject 1

82
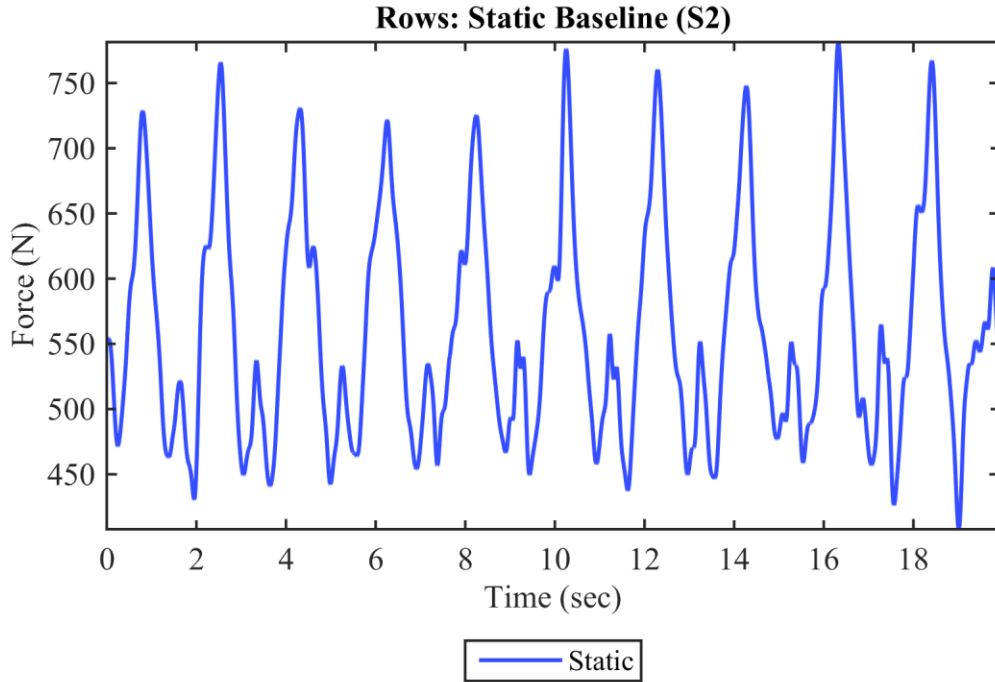
Figure 54: Filtered Resultant Force Data of Static Baseline Row for Subject 2
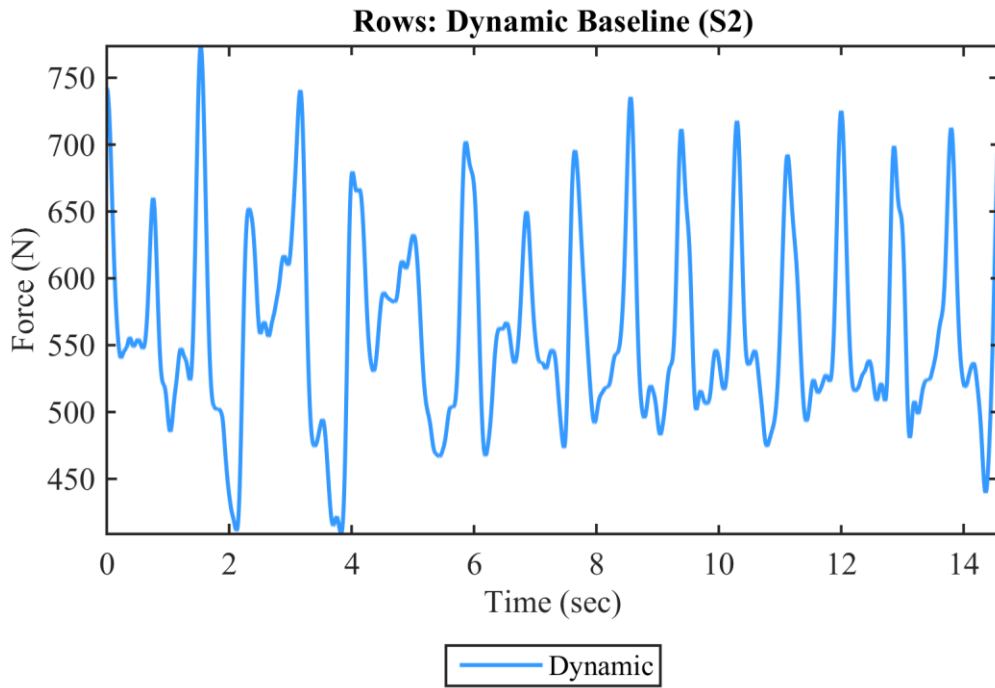
Figure 55: Filtered Resultant Force Data of Dynamic Baseline Row for Subject 2
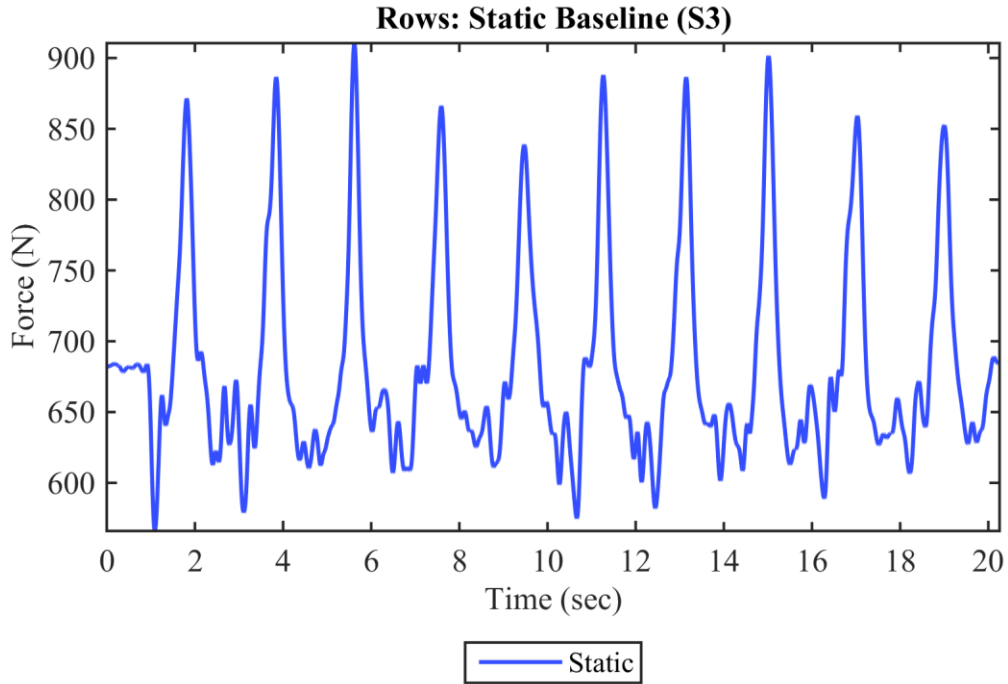
Figure 56: Filtered Resultant Force Data of Static Baseline Row for Subject 3
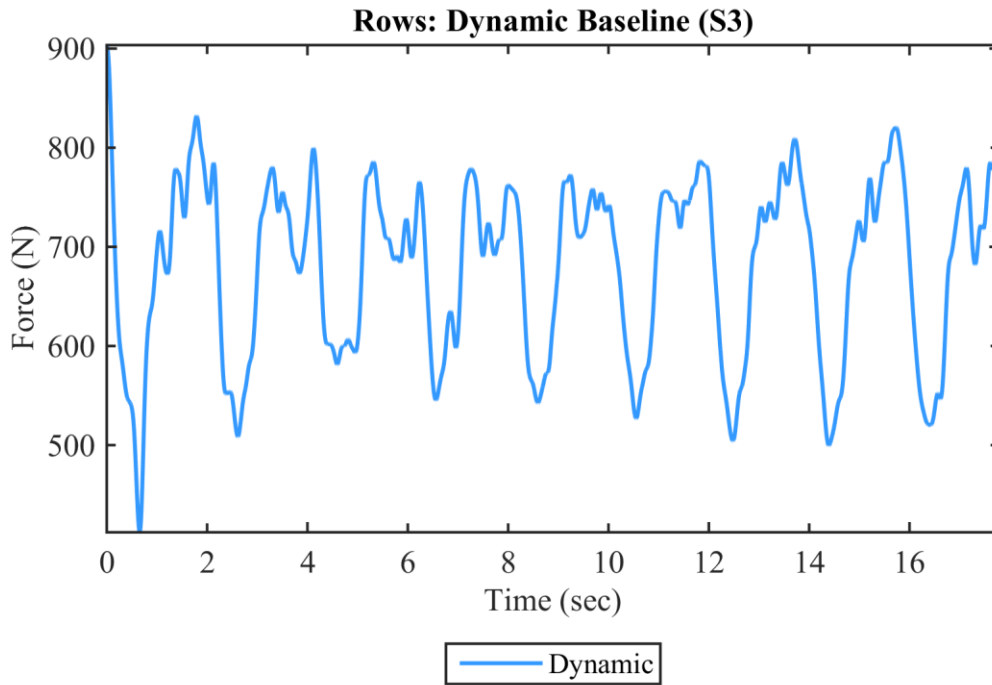
Figure 57: Filtered Resultant Force Data of Dynamic Baseline Row for Subject 3
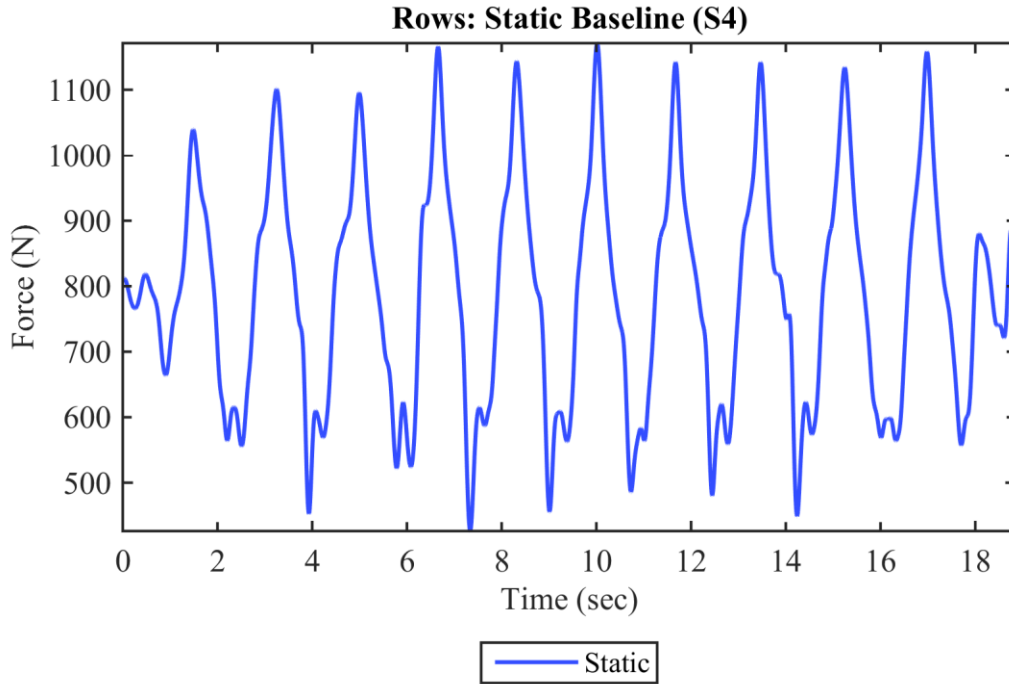
Figure 58: Filtered Resultant Force Data of Static Baseline Row for Subject 4
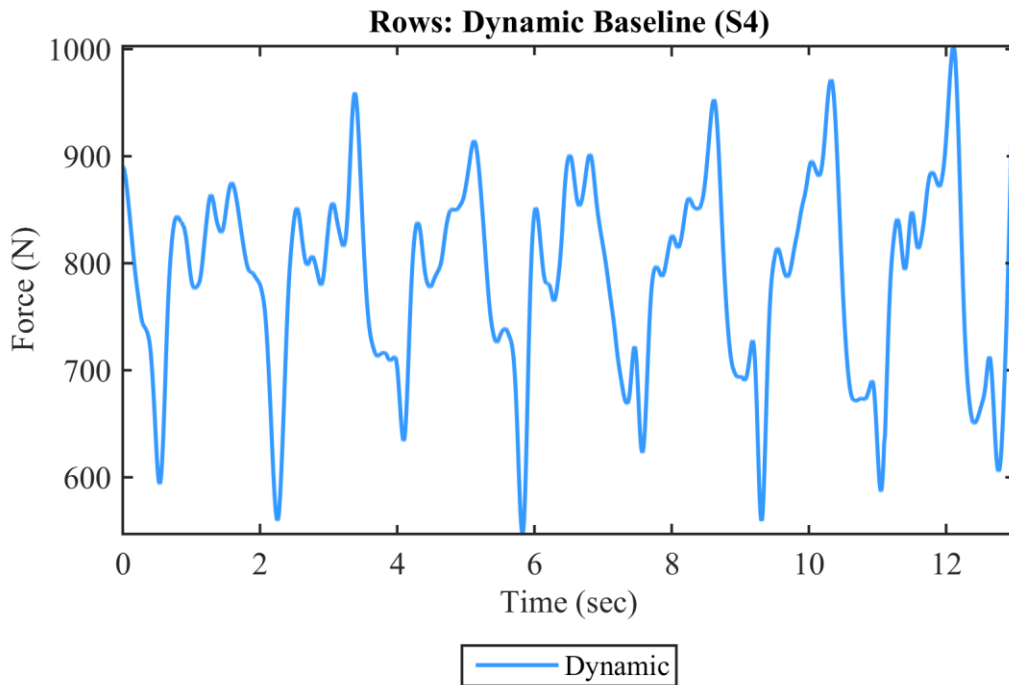
Figure 59: Filtered Resultant Force Data of Dynamic Baseline Row for Subject 4

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9.3.1.2 Maximum Forces and Force Ranges

Figures 60 and 61 provide the results for average maximum force and average force range, respectively, both corresponding to the Y component of ground reaction force. Graphs are provided for the heave only condition as well as heave + pitch. The Static Baseline trial is included on each for reference. For the Rows, the average maximum force with the heave only condition behaved similarly to squats, where maximum force increases with frequency. Dynamic baseline conditions have forces lower than the Static baseline condition in all cases except Subject 2. In the average force ranges however, all Dynamic baselines are higher than Static conditions and Subject 2 is still the exception. It is interesting to compare average force range for the Dynamic baseline in the heave only condition to all trials in the heave and pitch combined condition. All are directly comparable as they are all at baseline frequencies. When pitch is added in, the range of the Y component of force is smaller than in the heave only condition, in some cases. This is true for all pitch trials for Subjects 1 and 3.

Other individual variability is seen with the average force range of Subject 3's 0.35 Hz condition being higher than their 0.60 Hz condition. Subject 2's Static baseline is lower than all heave + pitch trials in average force maximum. Also, Subject 4's 0.5 degree pitch trial is higher than their Static baseline, 1 degree, and 3 degree trials in average force range.

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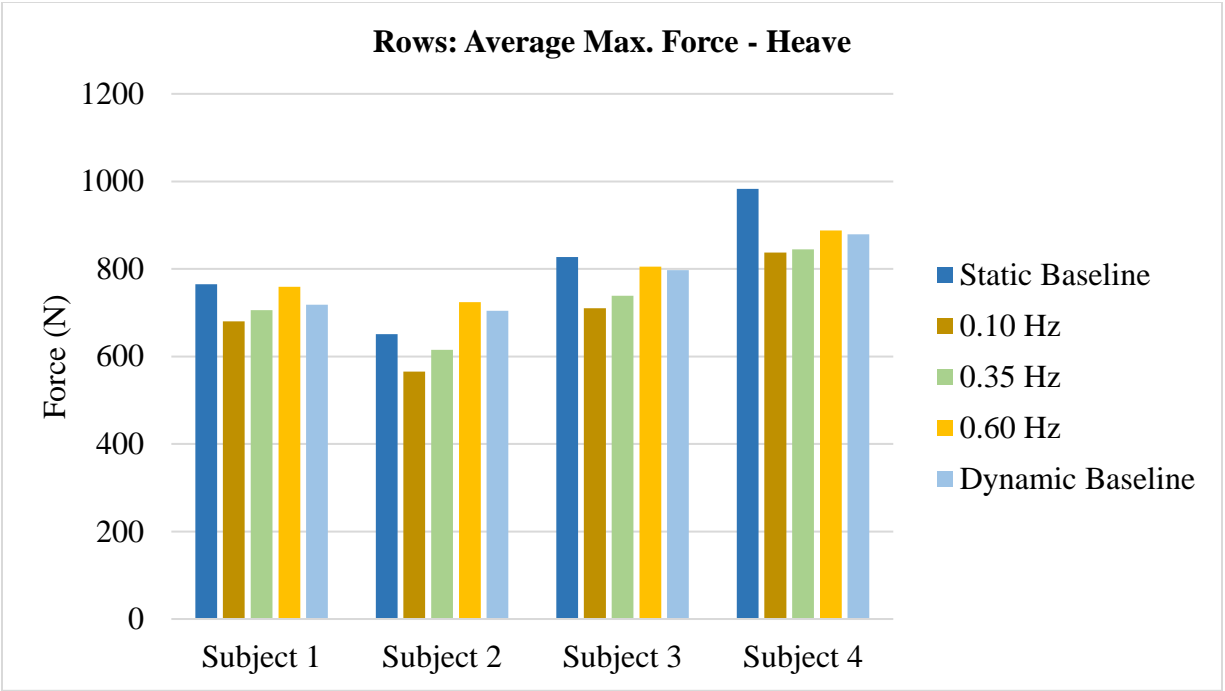
(a) Heave Only Condition
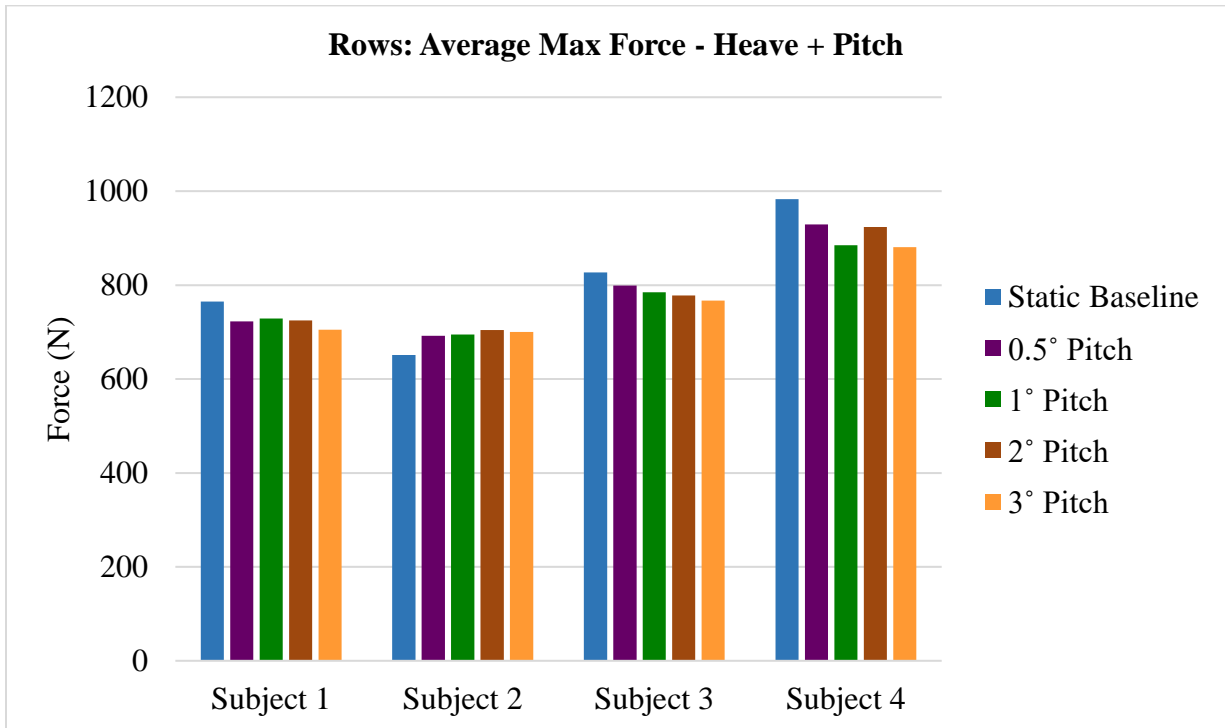
(b) Heave and Pitch Condition

Figure 60: Average of Maximum Force Across All Cycles in a Trial for Rows

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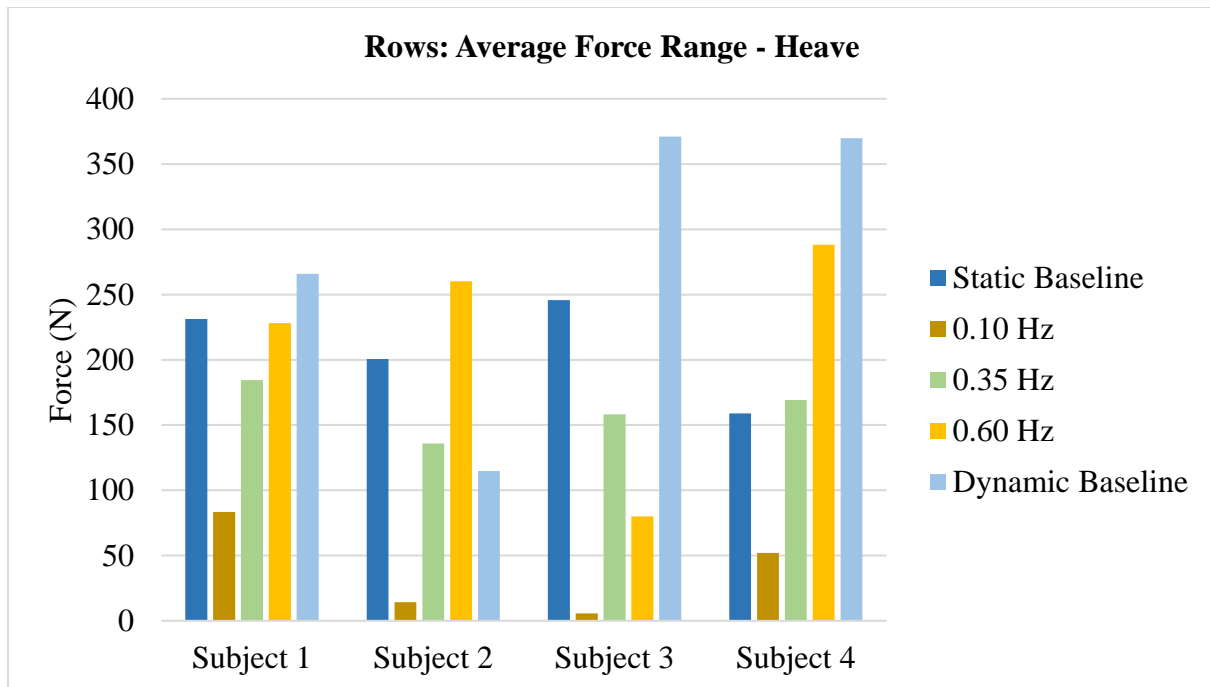
(a) Heave Only Condition
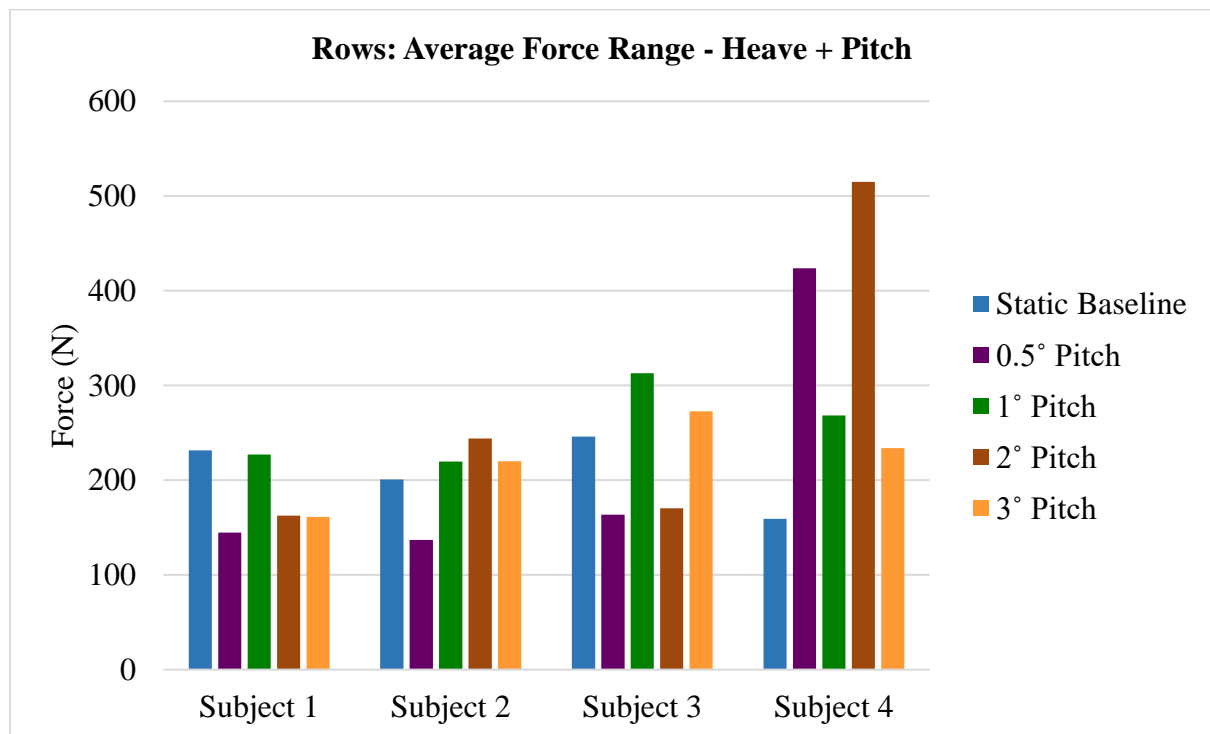
(b) Heave and Pitch Condition

Figure 61: Average of Range of Forces Across All Cycles in a Trial for Squats

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9.3.1.3 Force Frequency Matching

Just as with the Squat trials, the following graphs can be observed for insight as to how synchronized subjects were with platform motion. Graphs are provided solely for the heave only condition.
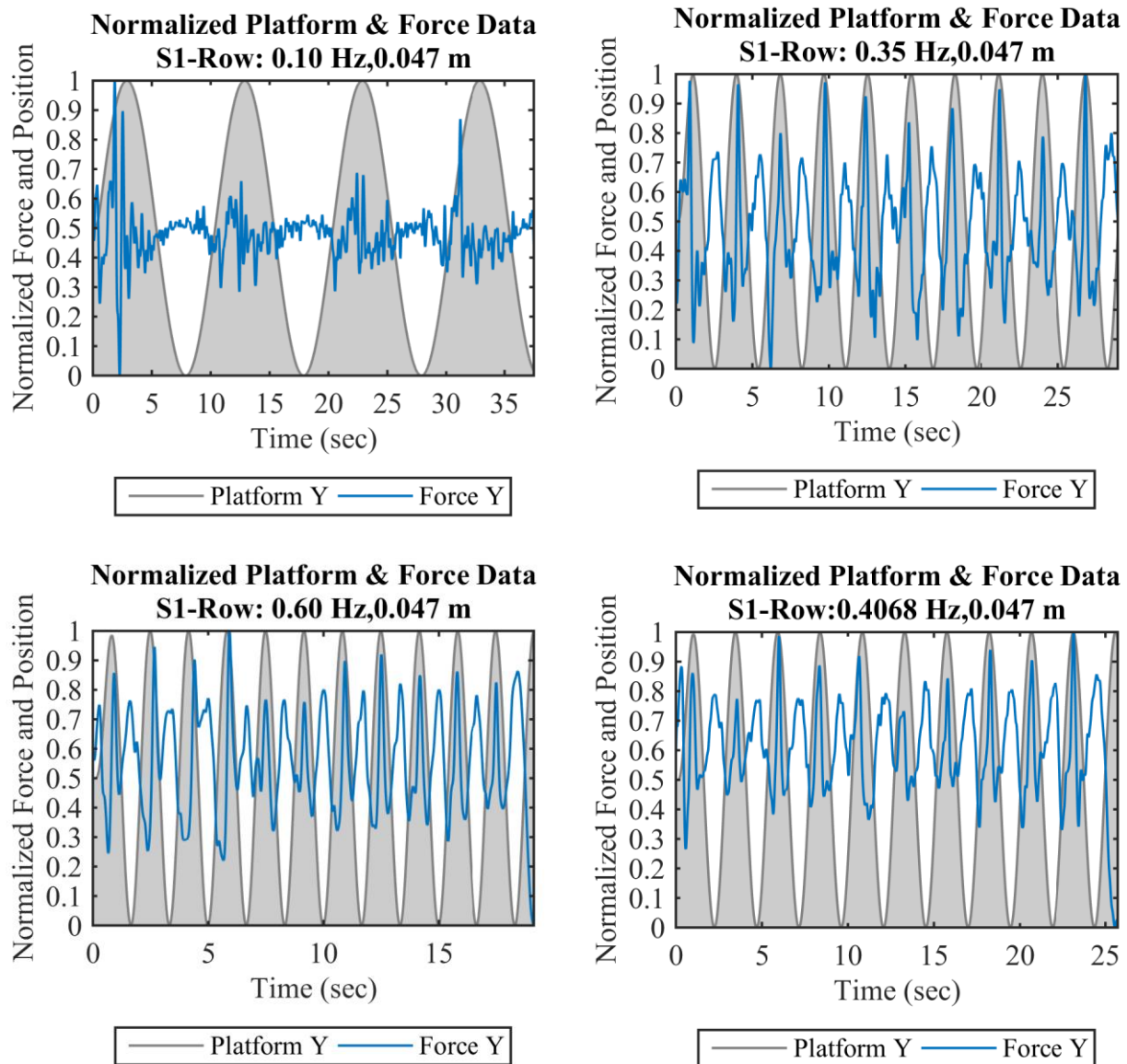
Figure 62: Synchronized and Normalized Force & Platform Row Data for Subject 1
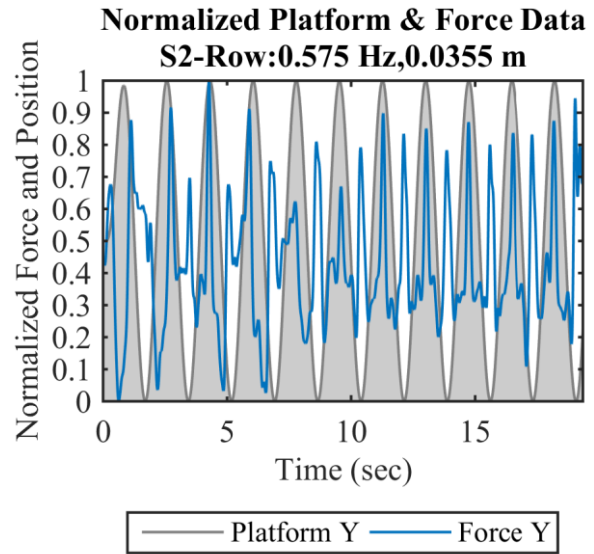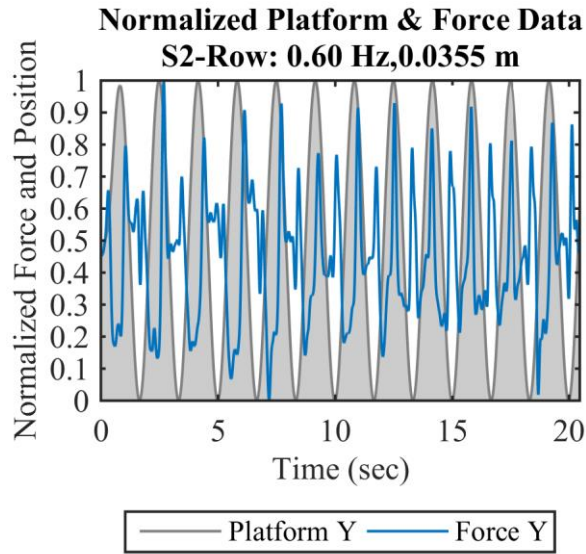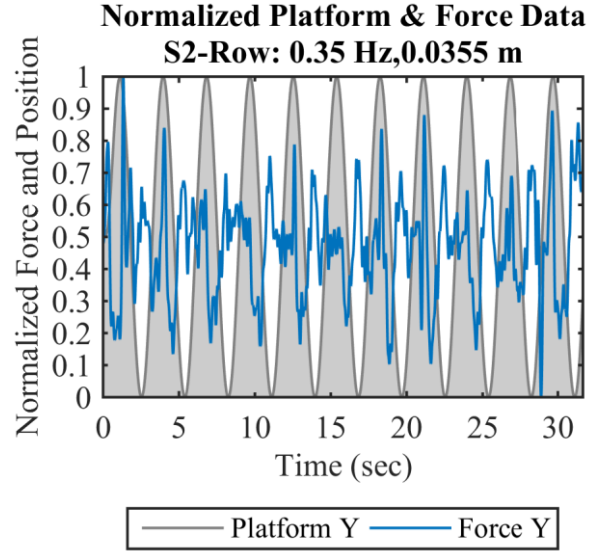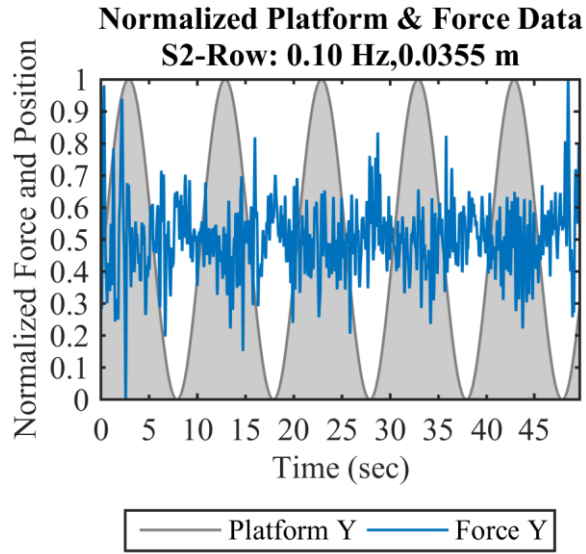
Figure 63: Synchronized and Normalized Force & Platform Row Data for Subject 2
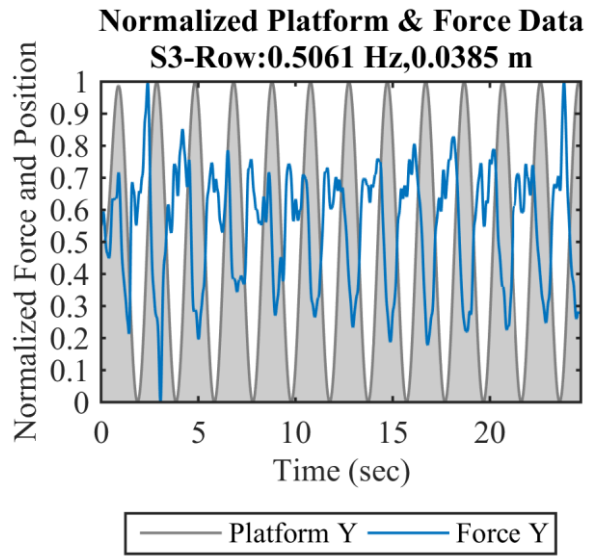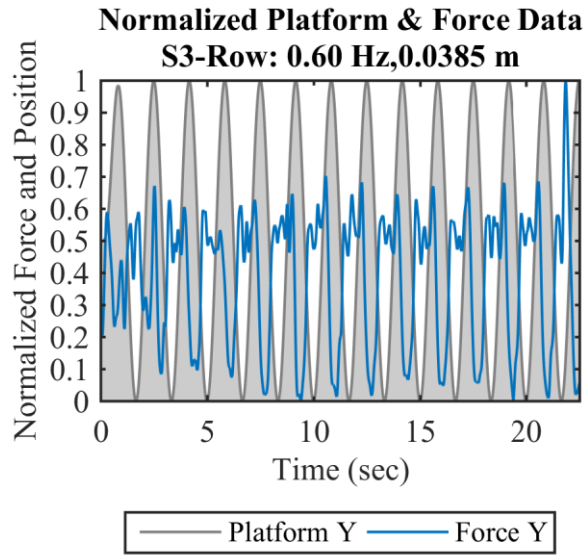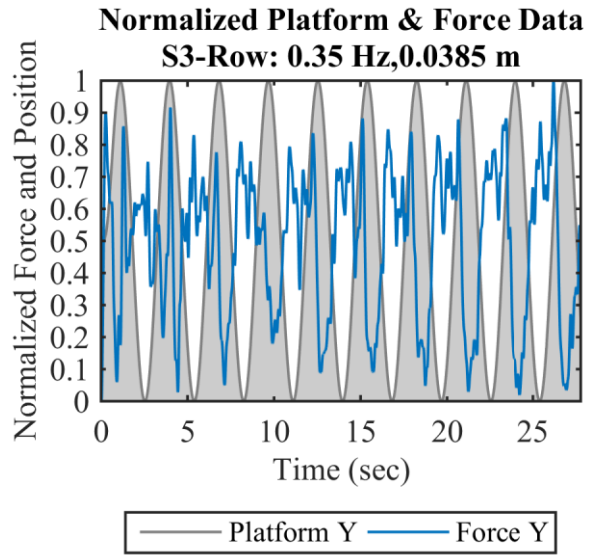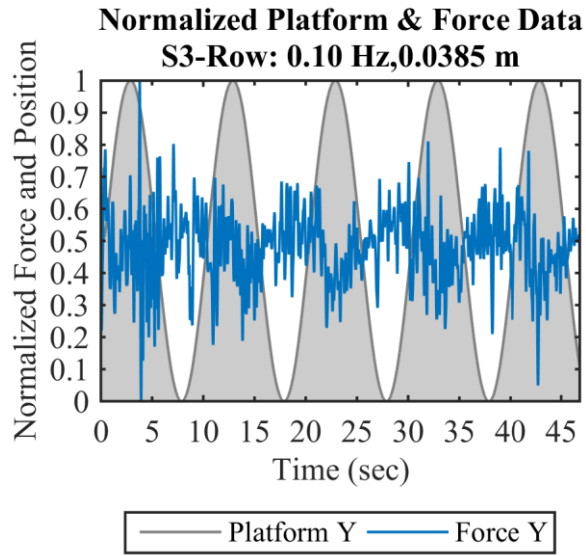
Figure 64: Synchronized and Normalized Force & Platform Row Data for Subject 3
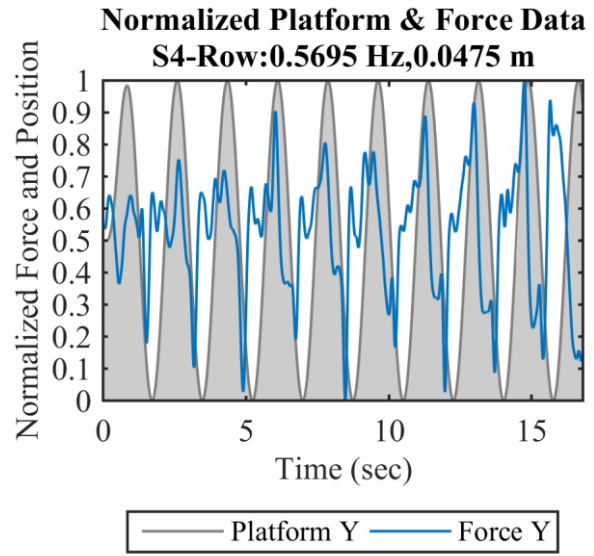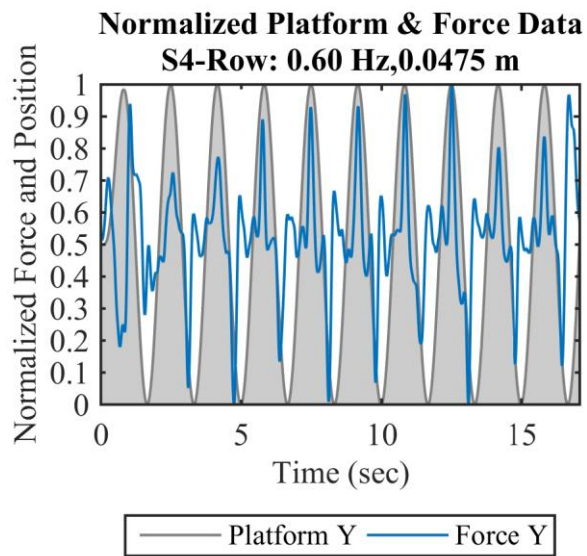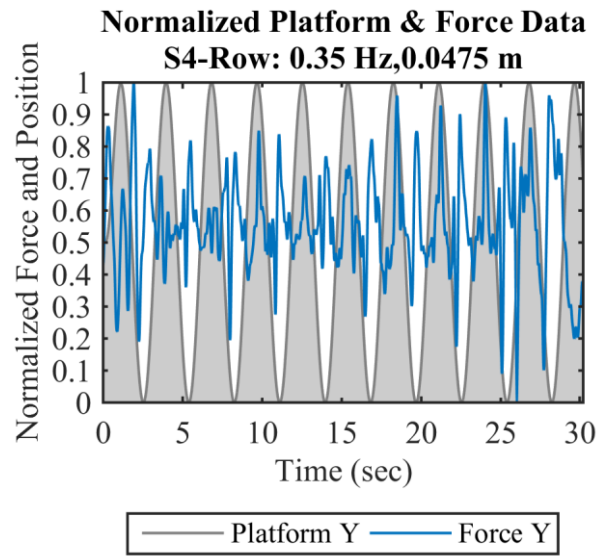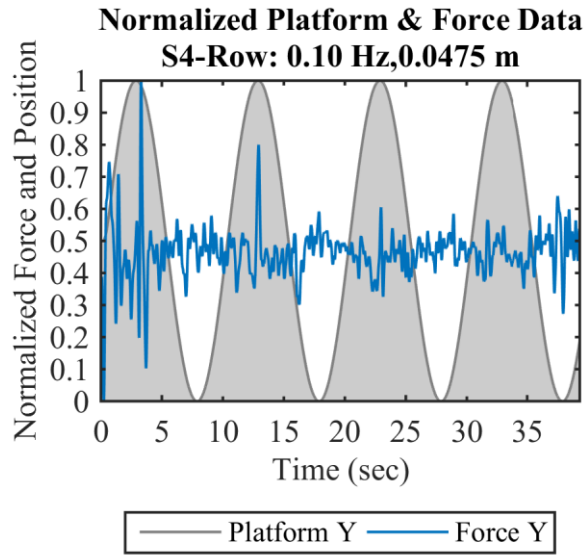
Figure 65: Synchronized and Normalized Force & Platform Row Data for Subject 4

9.3.2 Kinematic Outcomes

9.3.2.1 Knee Angle Trajectories
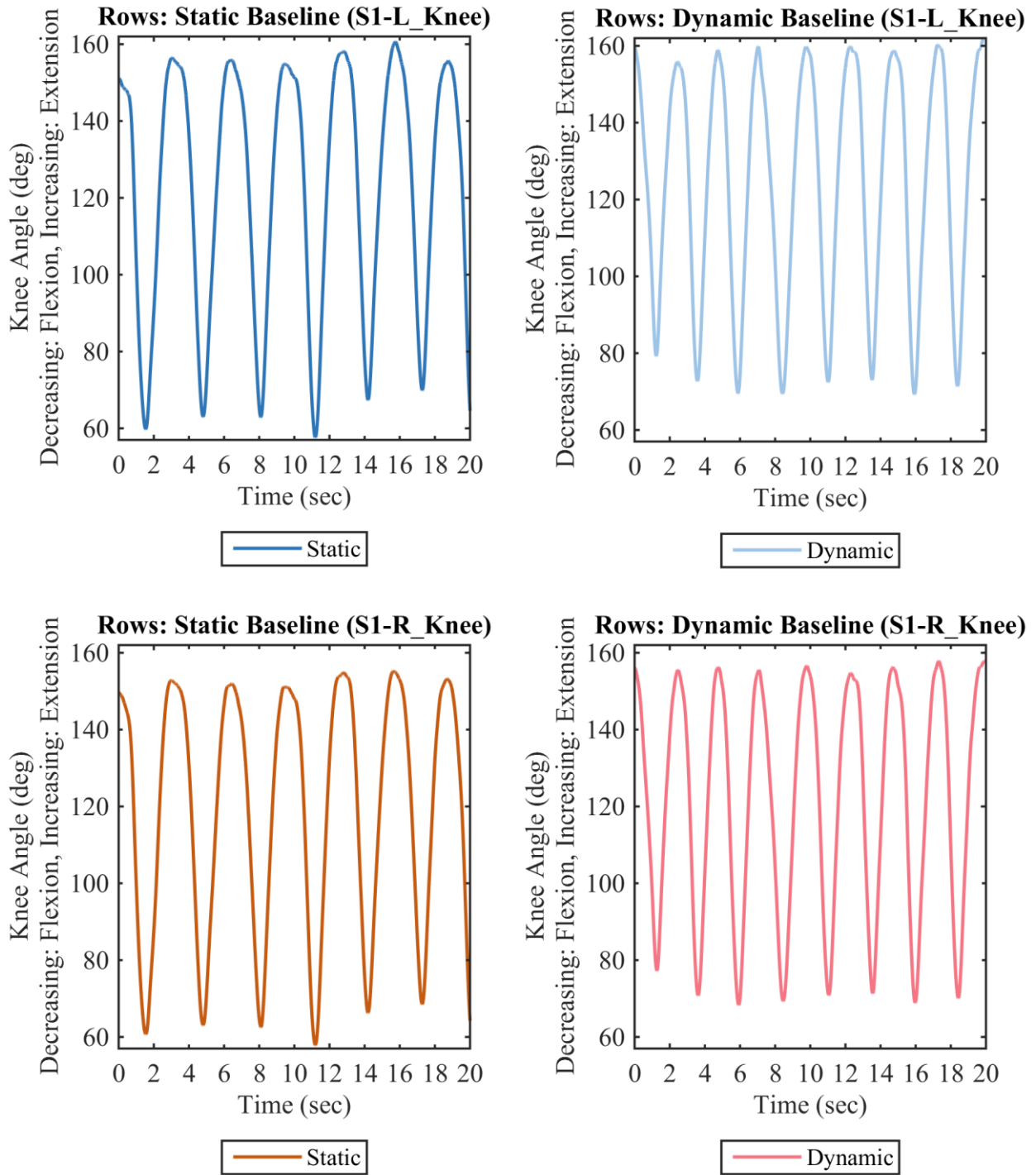
Figure 66: Subject 1 Baseline Frequency Rows with Static Platform (Left) and Dynamic Platform (Right). Left Knee Angle (Top) and Right Knee Angle (Bottom).
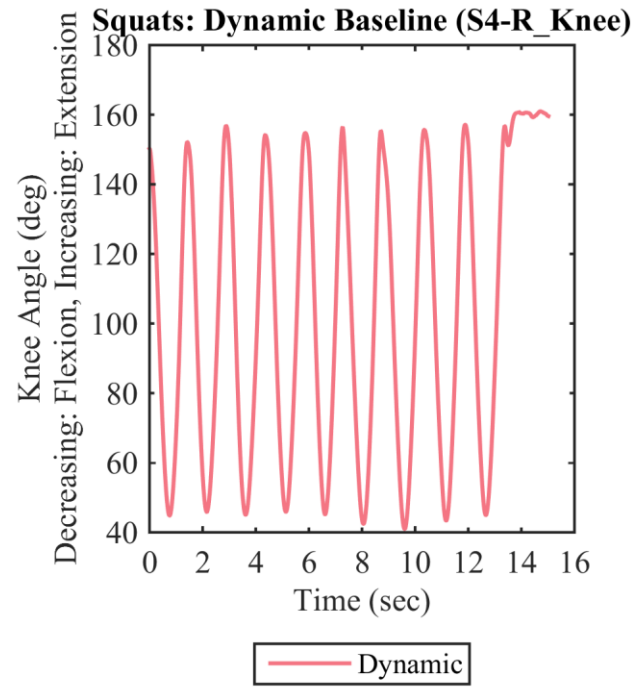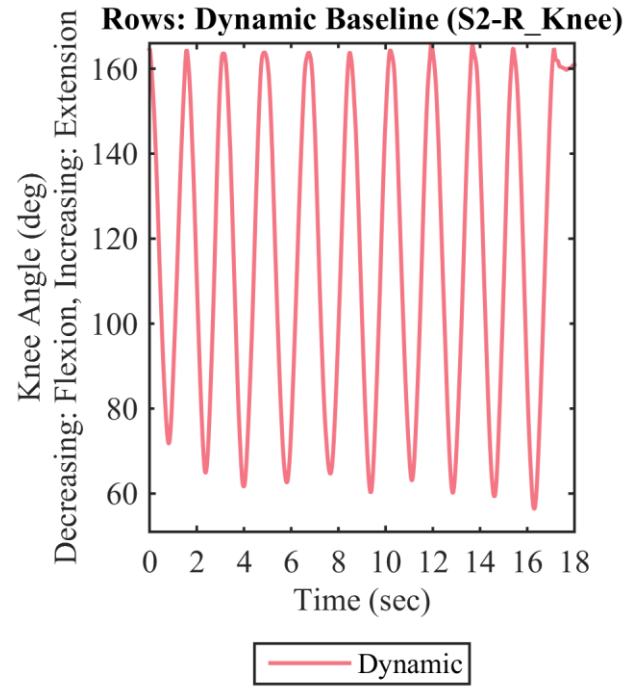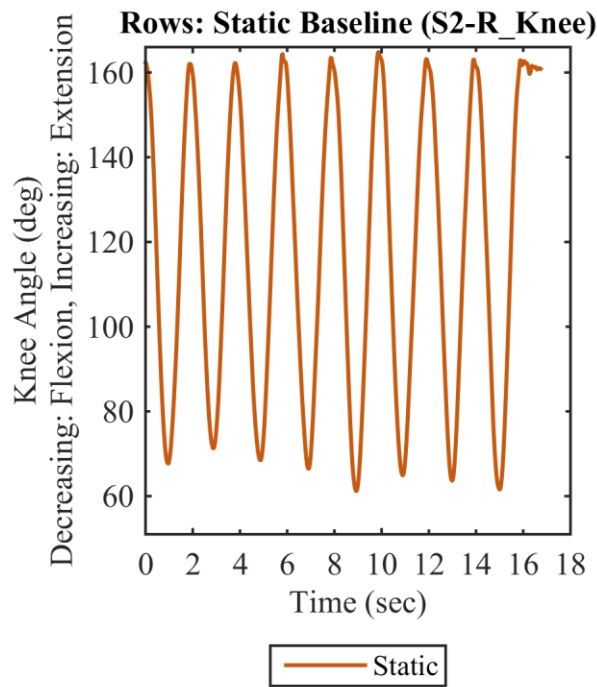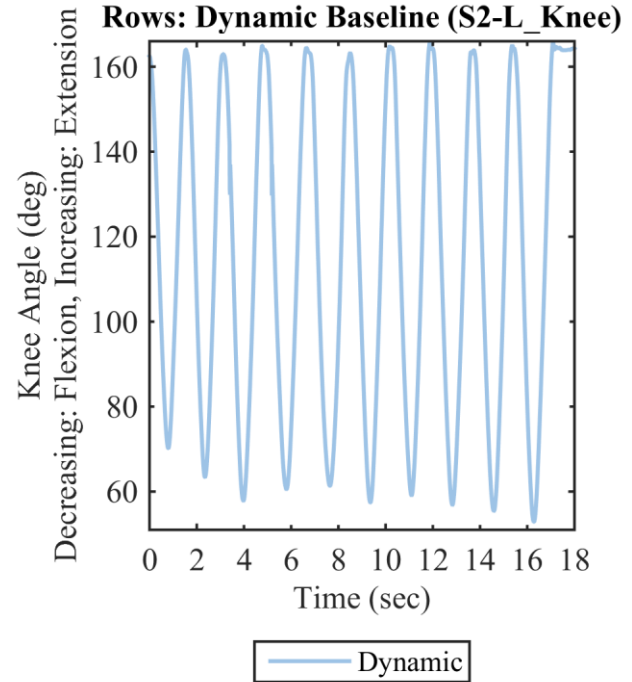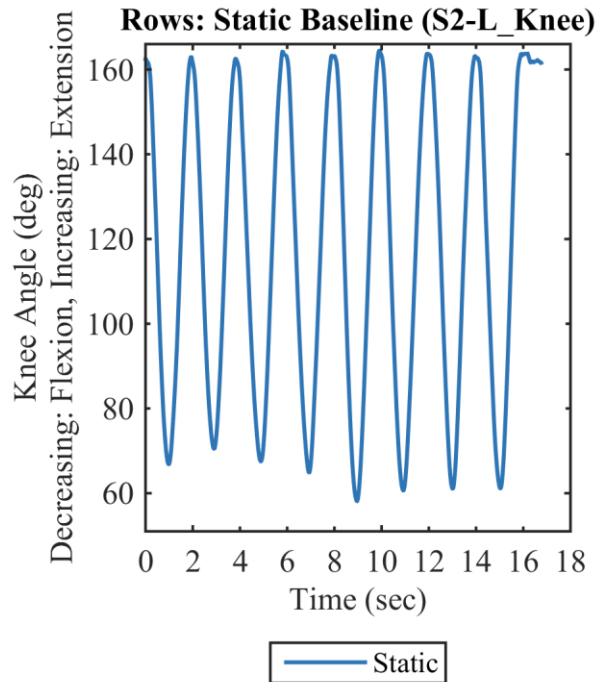
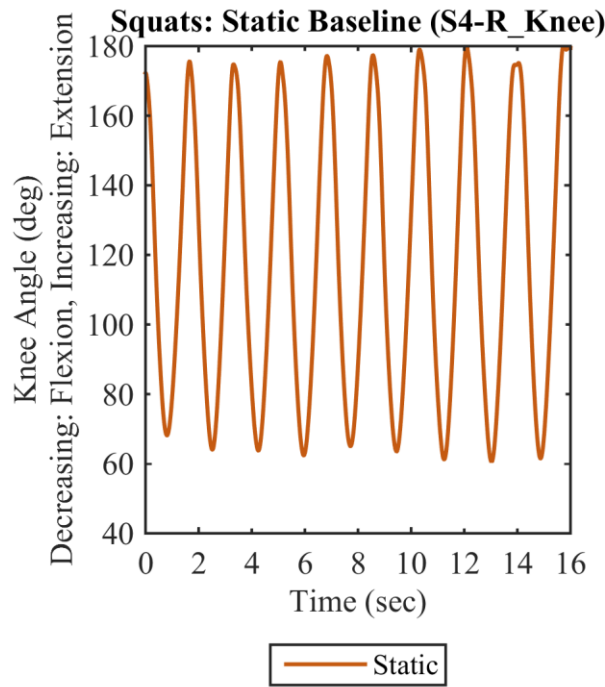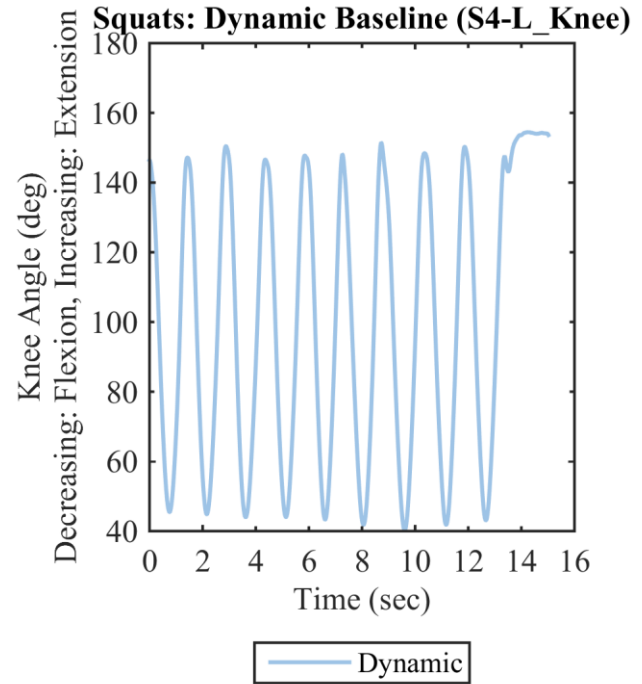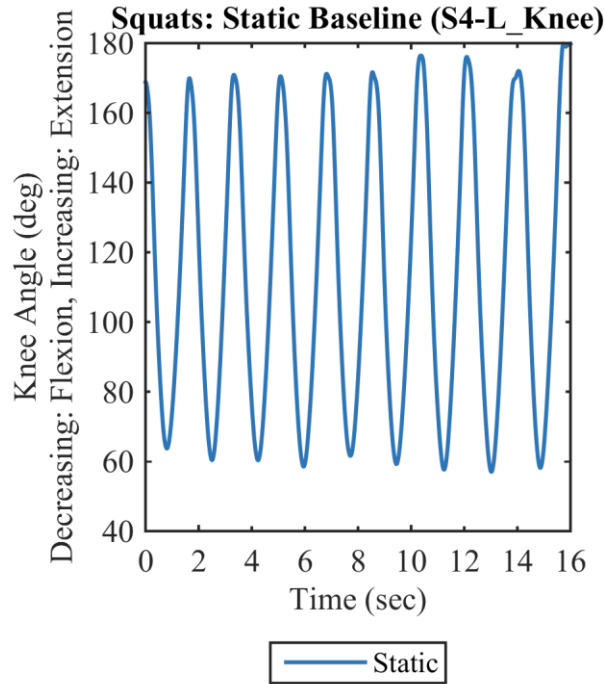Figure 67: Subject 2 Baseline Frequency Rows with Static Platform (Left) and Dynamic Platform (Right). Left Knee Angle (Top) and Right Knee Angle (Bottom).

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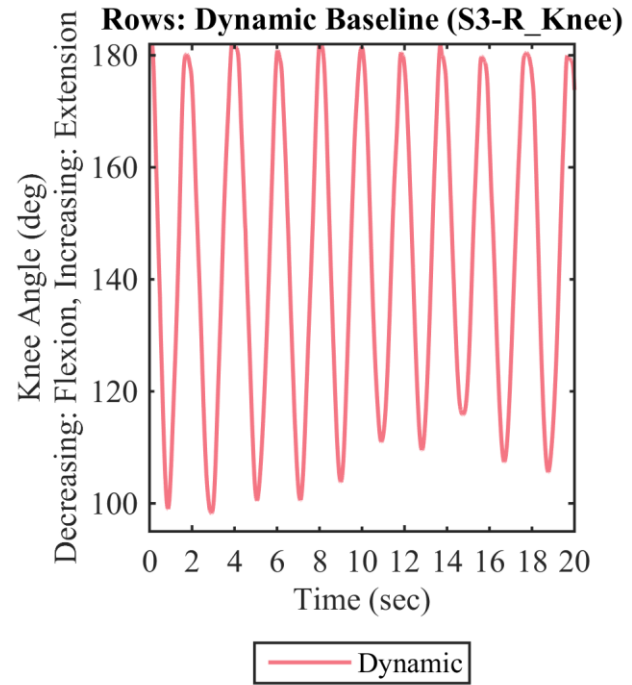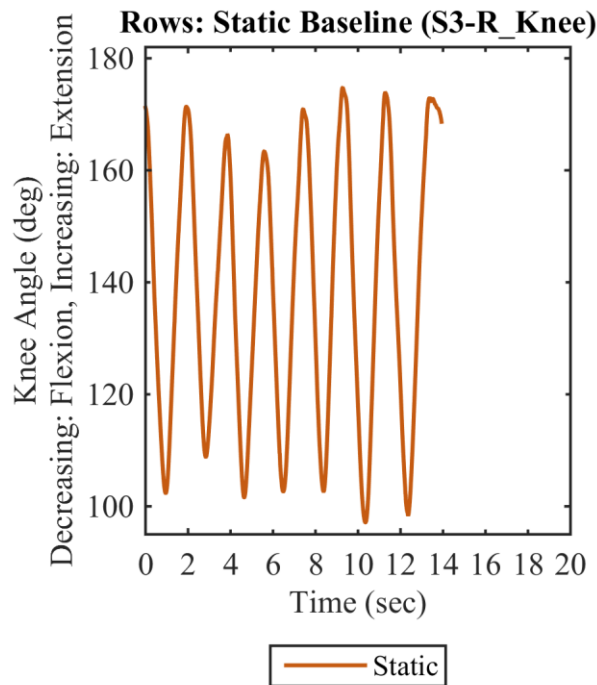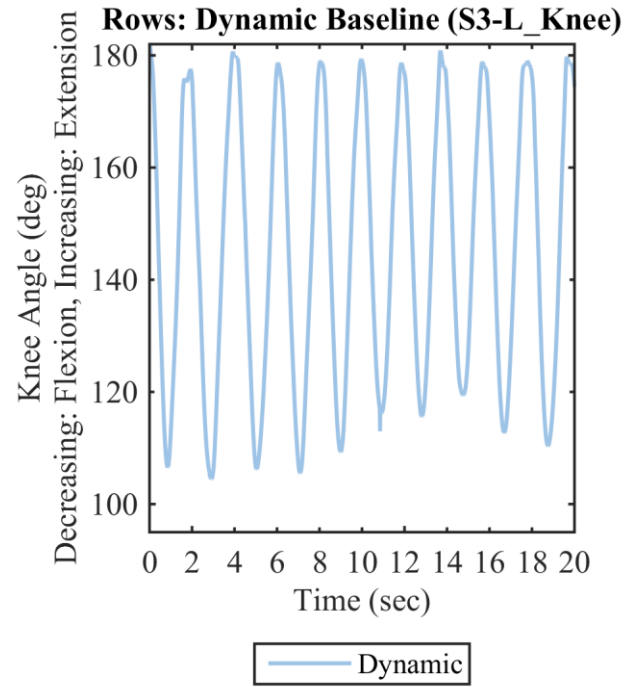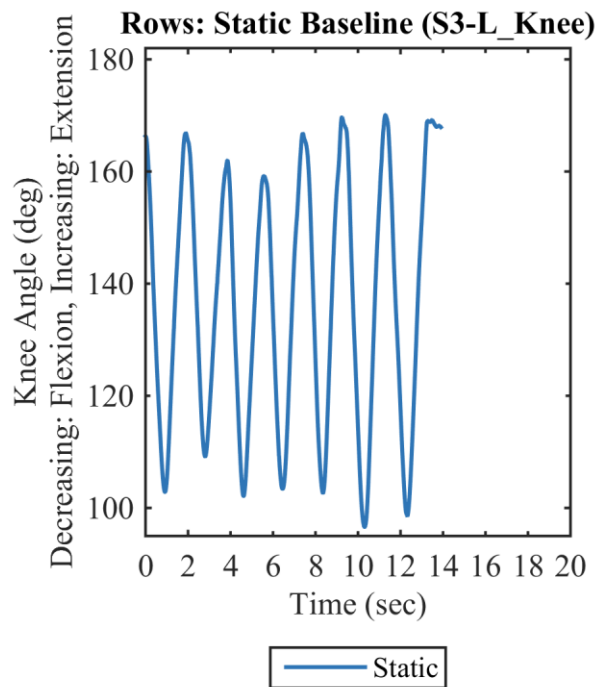
Figure 68: Subject 3 Baseline Frequency Rows with Static Platform (Left) and Dynamic Platform (Right). Left Knee Angle (Top) and Right Knee Angle (Bottom).

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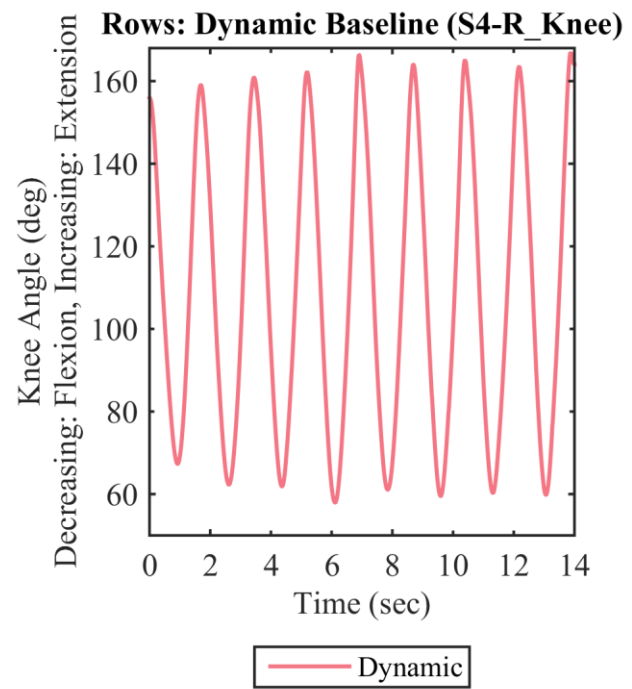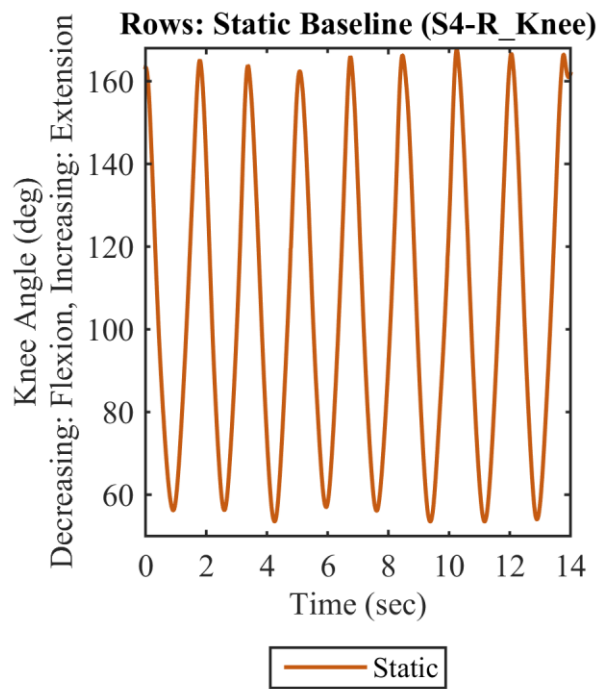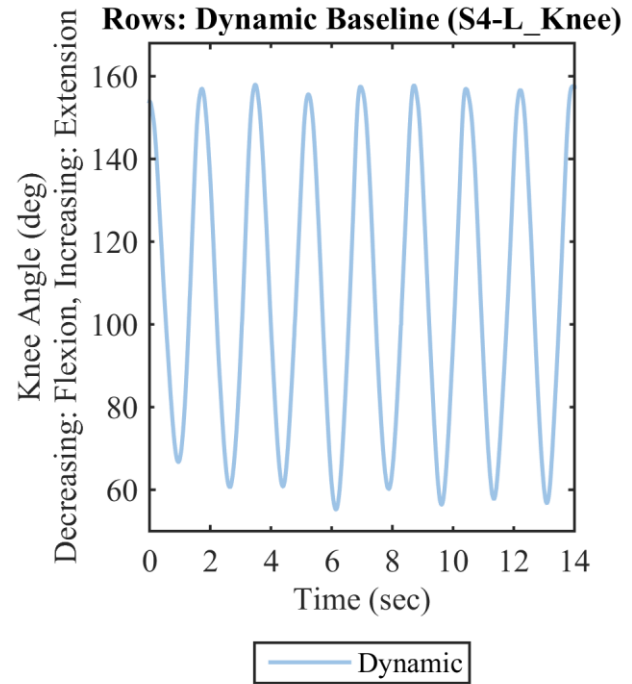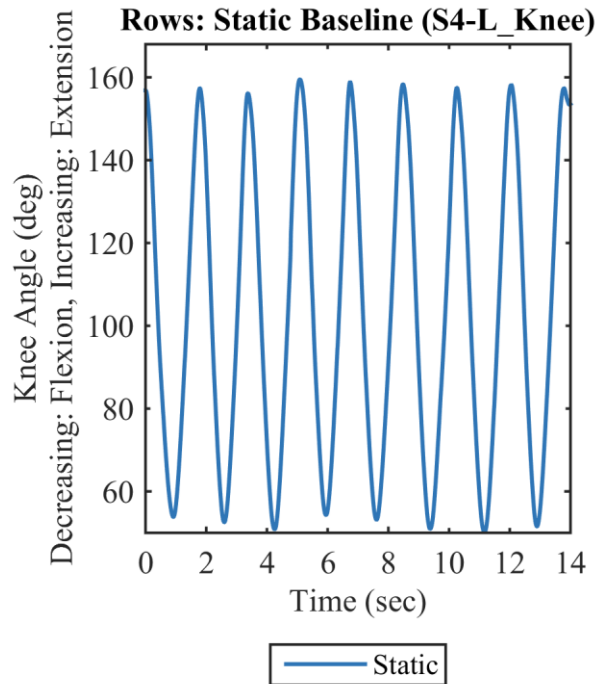
Figure 69: Subject 4 Baseline Frequency Rows with Static Platform (Left) and Dynamic Platform (Right). Left Knee Angle (Top) and Right Knee Angle (Bottom).

9.3.2.2 Knee Angle Range of Motion

The results for Knee Angle ROM for left and right knee during Static and Dynamic Rows are presented in Figure 70.
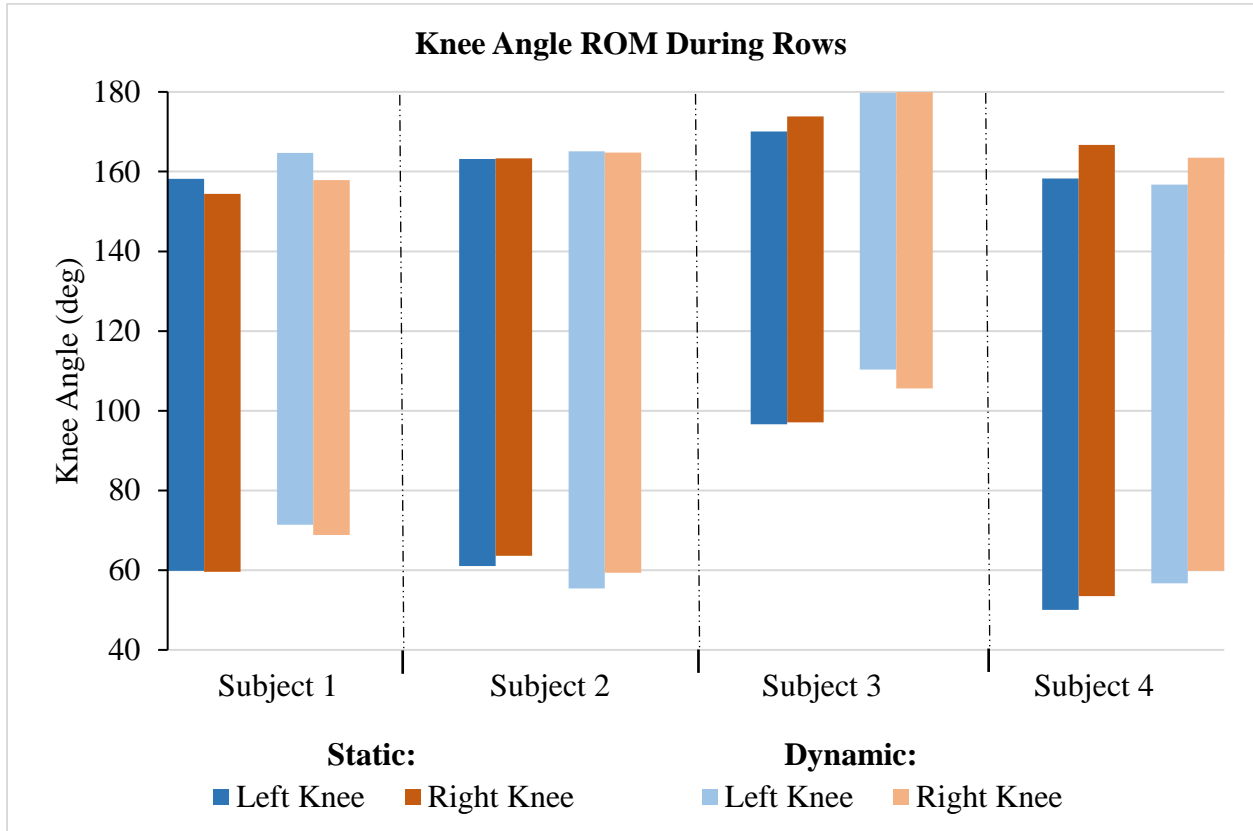
Figure 70: Average Range of Motion Across Exercise Cycles of Inner Knee Angle, Comparing the Static to Dynamic Platform During Rows

The Knee Angle ROM are similar between Static and Dynamic baseline conditions for Rows, where the maximum difference is 8.39% for Subject 4 on the Right Knee.

9.3.3 Questionnaire Responses

Four questions on the questionnaire pertained specifically to rowing, as described in 7.3.5 Questionnaire. Each subject's ratings are presented in Table 17. Additional explanation is provided in Appendix C.

Table 17: Questionnaire Results Specific to the Row Exercises

Question	Subject Designation			
	S1	**S2**	**S3**	**S4**
10	*I was able to complete a row as instructed while the platform was moving*			
	Agree	Agree	Agree	Strongly Agree
11	*I found it difficult to complete the rows while the platform was moving*			
	Strongly Agree	Disagree	Disagree	Strongly Disagree
12	*I was able to adapt to/match/sync with the platform motion during rowing*			
	Neutral	Agree	Neutral	Strongly Agree
13	*I felt that completing the row exercises while the platform was moving was comfortable*			
	Disagree	Neutral	Agree	Strongly Agree

Similarly to squats, Subject 1 varied from the group, noting difficulty of the rows. However, she still felt she was were able to complete the rows. Additional comments were provided and are included in Appendix C.

9.4 Observations

One of the key observations was that subjects used auditory cues to match platform motion, specifically the sounds from the actuators as the platform accelerates and decelerates. Subjects also noted this in the questionnaire responses included in Appendix C. Subjects 1 and 3 noted they used visual cues, watching the platform move relative to the background environment. The extent to which kinesthetic senses were used by the subjects throughout trials is unknown.

On a similar note, subjects seemed to not be able to feel the 0.5 degree heave + pitch condition (i.e., could not distinguish from the heave only condition). During study development, however, a test user noted they could feel the 0.5 degree pitch. A possible explanation for their sensitivity is that they were often on boats. However, other subjects brought forward that they had experience on boats on well, but they were not sensitive to the 0.5 degree pitch condition.

The "ramp-up" approach discussed in 7.3.4, Experimental Trials, worked well. Only one or two trials needed to be restarted due to the subject being unprepared for the trial condition. For

the majority, subjects were able to anticipate the frequency that platform motion would be at for an upcoming trial. Providing a starting position for the exercise seemed to help as well, allowing participants to usually start in synchronization with the platform motion within the first cycle.

It was difficult for the operator/study staff to observe frequency matching real-time. If a subject was out-of-phase, sometimes it could be identified, but it was difficult to determine the corrective action (e.g., going faster or slower in a part of the exercise cycle). Real-time analysis and feedback methods would improve the ability to correct this during testing. It was also observed that even if subjects were out of phase for a cycle or two, they usually regained synchronicity.

There was concern that subjects would not be able to maintain the "body over" position during rows while the platform was in the heave + pitch Dynamic condition. Though there were some cases where subjects stood straight up, when they were reminded of the body over posture and actively thought about it, they had the ability to maintain that form. Even so, there were inconsistencies in form observed in timing of row stages during the Dynamic platform conditions. Video and motion capture playback provided the best reference during the thesis work, but future analyses may further quantify these differences in form.

There was no loss of balance observed during the experimental trials. There were a few instances of loss of balance during a practice condition or during the extra experimental trials, but not many. Only Subject 1 noted they experienced motion sickness, and this was only when the platform was at large tilt angles. No subjects mentioned feeling dizzy or unwell during the testing itself and responded positively when asked in between trials if they are good to continue.

Also, subjects had the ability to match the heave platform motion during extra experimental trials where heave and pitch were set to different frequencies. Results are not reported here as not all subjects completed the extra trials.

CHAPTER 10: DISCUSSION

10.1 Discussion of Results

The cyclic force range and maximum forces exerted by the subjects, specifically in heave only conditions, behaved mostly as expected, increasing with frequency. This behavior was different, though, for Subject 4 Squats, where 0.35 Hz was significantly higher than the Static baseline (a frequency > 0.35 Hz). Also unusual was that Subject 3 Rows had a 0.60 Hz avg. force range smaller than the 0.35 Hz. These distinctions suggest individual variability in which frequencies are more stable for a person. The sample size should be expanded in future tests and multiple trials performed for each condition to expose more of these individual variabilities and possibly determine the causes. When directly comparing Static and Dynamic conditions at the baseline frequencies, it was found that the Dynamic platform decreased both the average maximum force across cycles as well as the average force range for most subjects in both exercises. This indicates that motions used in this study are promising candidates which could be used by a VIS for attenuations of forces. Also, this supports the use of the CAREN system motion platform as an analog for a VIS. There were exceptions, though, including the Dynamic baseline squat for Subject 4 in avg. max. force and avg. force range, row for Subject 2 in avg. max. force, and row for Subjects 1, 3, and 4 in avg. force range.

Results showed that subjects had the ability to match and synchronize with the platform motion reasonably well. The most out of phase results were the 0.60 Hz and Dynamic Baseline during Squat trials for Subject 4, where the subject had a tendency to stand ahead of platform downward movement and squat ahead of platform upward movement. Though most trials for all

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subjects had some out of phase cycles, these did not occur for more than 3 cycles in a row, with the exception being Subject 4 high frequency squats.

In general, the higher frequency Dynamic Baseline and 0.60 Hz trials were associated with cleaner, more distinguished load profiles (less peaks/troughs per cycle) compared to 0.10 Hz and 0.35 Hz trials. Though these additional peaks and troughs are of lesser amplitude than the major components attributed to the exercise cycle, their existence could still be of concern. It is considered that the frequencies of this "exercise noise" might still fall into the unwanted vibratory region of the ISS, as mentioned in 2.2.1 Vibratory Environment, and future space vehicles. Since these are also forces which the human may have less control over, a real VIS might need to impose thresholds which prevent instability. A VIS might need to handle forces not attributed to the bulk motion of the exercise differently, in a way such that the exercise is either unaffected or benefitted by platform motion. This research did not explore closed-loop control of the platform motion, but it was considered for future work.

Knee Angle ROM was similar between Static and Dynamic Baseline trials for both squats and rows. This suggests that exercise form should be able to be maintained with VIS motion, at least in these small amplitude conditions and ranges of frequencies. It is noted that there are only slight decreases (0.78% - 8.39%), from Static to Dynamic, in range of motion of knee angle across subjects, where the exceptions are that Subject 3 had a greater decrease (15.75% for Right Knee) in the Squats and Subject 2 actually had a slight increase (7.36% on Left Knee and 5.79% on Right Knee) in the Rows. The ROM midpoint does shift most noticeably for Subject 4 Squats, downward from Static to Dynamic in that case. The total ROM appeared to be maintained, though the data provides that knee flexion was greater (lower minimum ROM value) and knee extension was smaller (lower maximum ROM value) in the Dynamic case for Subject 4. Checking against video,

this difference was not apparent. It is possible that this result had error attributed to the functional skeletal model or kinematic fit processing in Nexus. As was noted in 8.2 Kinematic Data Processing, a different processing method was required to be used on Subject 3 Dynamic Squat and Subject 4 Static Squat. Notice that these are the trials with the notable distinctions presented here. Future work will include additional verification of results through obtaining joint angles using other models, software, and techniques.

It is also worth noting that ground reaction forces and knee angles obtained in the Static Baseline trials are reasonable, considering the background provided in 2.3 Biomechanics of Exercise. Following calculation of the acceleration of the subject's center of mass, squat force data can be further verified computationally. Squat knee angle, as mentioned, should be near the instructed value. Squat Knee Angle ROM from this study ranged from approximately 92° to 115°, averaging around 105°. While the instruction was for 90°, these deviations can be expected. Regarding rows, normalizing the average maximum forces to the subject's body mass is comparable to the normalized peak foot forces in Buckeridge (2013) [23]. However, knee angle ROM for rowing was smaller in this research. The results are reasonable though, considering the unconventional configuration, where standing is required with feet on flat ground (90° ankle angle) and no external resistance is applied, though the subject had to support their own body weight.

10.2 Limitations and Future Improvements

As mentioned in Chapter 7, Experimental Design Implementation, baseline amplitude and baseline frequency for each participant was determined for each exercise via off-platform measurements, a process which is more susceptible to human error. Although both parameters could be determined, possibly more precisely, from the Baseline Trial (exercise performed on the static CAREN platform), this would significantly extend the session time required for study

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participants since determining height difference from motion capture and frequency from force plates would require processing time. Also, given resources available on the system for data processing (limited to LibreOffice), it was determined to be in the best interest of the study to pursue an alternative to processing data to obtain baseline amplitude and frequency. It was considered that participants might deviate from their Baseline Trial during subsequent trials and that deviation could be similar between off-platform measurements and those which could be obtained from the Baseline Trial. Still, some improvements to this process could include using a script module to calculate an average amplitude and frequency in real-time and save to a text file which could be viewed and the values implemented.

Section 4.4, Environment Distinctions, discussed how the exercise motion specifically should be mostly representative of form in a microgravity environment due to the alignment of the gravity vector with the principle axis of exercise. To extend on the transferability of the work, EEDs may provide constraints which simulate gravity. Nevertheless, the kinetic and kinematic results are expected to be different in a microgravity environment, especially considering documented differences in squat kinematics between ISS and ground-based studies using ARED [31]. However, this is acceptable as there is no current analog without limitations. For example, the Active Response Gravity Offload System (ARGOS) at the Johnson Space Center provides inertial effects that would be experienced while moving in various reduced gravitational environments, but users must still support body segments against Earth gravity. The Neutral Buoyancy Laboratory also provides the feeling of microgravity, but motions have resistance against water. Parabolic flights provide a closer analog to on-orbit conditions, however the duration of microgravity is generally limited to less than 30 seconds at a time. All microgravity analogs have benefits and tradeoffs. Results from testing in various analogs can be compared to

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find the answers. Hence, this test can be combined with the other methods used in human spaceflight research to increase the scope of knowledge. This research provided the Dynamic platform condition which other analogs do not.

The sample size in this study was small. However, small sample sizes are typical for collections done for computational human modeling work. Especially for a proof-of-concept, the small sample size was appropriate for the start of this work. The small sample size limits the conclusions which can be made and explanations for the results, but observation of the results can still tailor parameters of interest to test in future work. Variability was seen across subjects even with the small sample size. However, this study compared each subject to their own baseline conditions and did not aim to make any cohort conclusions.

10.3 Contributions

The contributions of this research to ongoing work in human spaceflight are highlighted here. These contributions may continue to expand as the data obtained in the study undergoes further analysis and use. All NASA Technology Roadmap areas mentioned earlier were addressed. The subsequent text elaborates on the contributions to those areas.

10.3.1 Enhancing VIS Design Process

Currently, exercise data from facilities with fixed ground force plates are used as inputs to models and analyses for VIS design. This research showed that the force profiles associated with exercise differ when on a moving platform, even when humans are closely synchronized with the platform motion (as would be the case with final VIS flight hardware). There are variations in both amplitude and frequency of forces during an exercise repetition. When the goal is to isolate certain frequencies, this information is important to take into consideration in VIS design. Hence, data from this research can be incorporated into the VIS design process to improve the validity of the

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input responses. Current data analyses may be too conservative by only incorporating fixed ground force plate data. The results from this research can also help in the assessment of how conservative existing analyses may have been. Comparing results can help identify areas in the analysis methods which may need to change.

10.3.2 Modeling

Extending on 10.3.1, real experimental data are needed to improve models of VIS dynamics as well as biomechanical models. This research contributed to the data available for use by NASA's Digital Astronaut Simulation group to increase the validity of models. The ground reaction forces measured in this research can be used as external forces in inverse dynamics analyses which are used to determine joint loads in biomechanical modeling. Beyond that, since two force plates measured the separate forces at each foot, asymmetry can be incorporated (another area where available data are limited). This research also provided joint angle trajectories using the Human Body Model Functional Skelton Calibration in Vicon Nexus as well as from the Kinematic Fit feature. When inverse kinematics processes are run in the biomechanical modeling software currently used by the NASA's Digital Astronaut Simulation team, OpenSim (NCSRR, Stanford, CA, USA), joint angles can be calculated. Having multiple methods by which joint angles were obtained will help in the verification process for the biomechanical models being used.

Another interesting use of the data available from this research could be to use the motion capture data to drive models, but disable gravity in the software to observe the forces involved in the environment of greatest interest. This can be accomplished computationally, as well, by removing the acceleration of gravity from force data collected. Simulations of VIS motion needed for a particular exercise motion could be compared with the resulting exercise motion from the

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VIS motion generated in this study. In general, there are many combinations of using the motion capture and force data from this research to aid in enhancement and verification of models.

10.3.3 Exercise Countermeasures

The joint angles and ground reaction forces can be used to help assess exercise efficacy under dynamic platform conditions. These data can be used to help develop exercise regimes that maximize benefits. This idea is extended in 11.2 Recommendations. Following the analysis provided by biomechanical modeling, joint loads and muscle activation can be estimated and exercise efficacy further assessed. The motion capture marker trajectories and the forces measured at each foot from this research provide the foundation for additional biomechanical analyses.

10.3.4 System Optimization

This research provided information which can jointly be shared between system components (VIS, exploration exercise device, and human). By combining knowledge and efforts in the system design, the optimal parameters for both exercise benefits and VIS design and control can be determined. For instance, the optimal exercise frequency can be found by considering what force amplitudes produced are acceptable from both the standpoint of the exercise countermeasure as well as the VIS.

10.3.5 Other Fields

This research may also contribute to fields outside of human spaceflight and it has laid groundwork for future research in these areas. Dynamic motion of the ground is experienced by personnel on ships, including military personnel for long stretches of time. This research can be applied to strength training in that environment. Future studies using the CAREN system could help with general training for living and working on boats, ships, and other marine vessels. Another applicable field is rehabilitation on Earth. Dynamic platform motion could provide targeted ground

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forces and even push patients to complete motion at target frequencies. It could assist in balance training, making completing activity on solid ground easier. Rehabilitation related studies are primary uses of the CAREN system, and the methods applied in this research can be transferred to those studies. This research could also be applied to a new kind of exercise training on Earth where resisting a moving platform could strengthen muscles more so than exercising on static ground. Sports training for athletes could be of interest too, especially for sports with ground movement such as surfing, wakeboarding, skiing, snowboarding, and the like. Future studies could explore these areas.

CHAPTER 11: CONCLUSIONS

11.1 Conclusions

This thesis research functioned as a proof-of-concept for a test environment capable of collecting data to support spaceflight countermeasure work from both the perspectives of human biomechanics as well as an exercise VIS. This research quantified the human-VIS interaction by providing kinetic and kinematic data, at individualized amplitudes and specific frequencies of interest, with simplified prospective VIS motion along principle axes of squat and row exercises. This provided quantitative measures of the bi-directional effect between a VIS and human. This research compared each subject to their own baseline as the ideal exercise forces and form to target, allowing for direct comparison of each subject in Static platform and Dynamic platform conditions.

In summary, all objectives and specific aims of the study were met. Full functionality of platform motion control in both isolated and combined degrees of freedom was achieved. Human subject testing was completed successfully. Conditions and measures were established to meet the aims of quantifying external force differences and joint angle differences between Static and Dynamic platform conditions.

11.2 Recommendations

It is recommended that the CAREN system serves as a resource for future studies in this field as it provides an analogous system to VIS, allowing for data acquisition as well. Observations brought forward that auditory cues may enhance one's ability to synchronize with platform motion. This is a method which could be considered, should a human need to adjust to a dynamic ground

response. This research provided additional evidence that the Y component of force is larger than the others in these exercises. Configuring a VIS longitudinally in space vehicle modules, so that the Y component of force is directed to the ends of the modules, rather than the surrounding walls, may address the problem in a different way.

A question was posed during this research: if a VIS is effective, are you getting as good of a work out? Exercise physiologists should consider if the maximum allowable loads, to which a VIS reduces the forces, are still adequate for the exercise. This research showed that athletic persons have the ability to exercise at specific frequencies, which could likely be even further improved for consistency with more training. Therefore, it may be worth considering exercise at frequencies where forces are more target specific. An alternative may be more repetitions of exercise at lower forces, though this may be less ideal for strength training. Of course, an EED may provide additional external forces and constraints on the body that result in adequate internal forces to promote muscle and bone strength. In general, it is recommended to ensure that the VIS does not remove what the exercise device is designed to provide. If that is unavoidable, then new exercise regimes and system uses should be established. Exercise efficacy may be able to be assessed through finding work and energy of human movement, using methods such as those described in "Kinetics of Human Motion" by Vladimir M. Zatsiorsky [32].

It is highly recommended that the human-EED-VIS system be considered as a whole, where design requirements and constraints are shared between each part. Otherwise, a well designed VIS could render an exercise regime ineffective or an exercise regime could exist outside of the VIS limitations and create undesired vibrational effects. There is also a possibility that exercise paired with a dynamic platform (at certain responses, frequencies, and synchronization phases) can enhance the exercise and also be acceptable from a vibrational standpoint. It is

recommended that exercise physiologists further examine the varied force profiles from this research and consider positive, negative, or neutral effects.

11.3 Future Work

Future work will include further analysis of existing data, for example, studying other joint angles, finding subject center of mass trajectories, and other biomechanical analyses. New tests will be conducted where other amplitudes, frequencies, and exercises may be incorporated. These tests may incorporate additional degrees of freedom. To further contribute to answering questions surrounding active VIS concepts, closed-loop control methods may be attempted, using force plates and/or motion capture to drive platform motion.

REFERENCES

[1] Williams, D., Kuipers, A., Mukai, C., & Thirsk, R. (2009). Acclimation during space flight: effects on human physiology. *Canadian Medical Association Journal,180*(13), 1317-1323. doi:10.1503/cmaj.090628

[2] Mars Facts | Mars Exploration Program. (n.d.). Retrieved March 07, 2018, from https://mars.nasa.gov/allaboutmars/facts

[3] Smith, S. M., Heer, M. A., Shackelford, L. C., Sibonga, J. D., Ploutz-Snyder, L., & Zwart, S. R. (2012). Benefits for bone from resistance exercise and nutrition in long-duration spaceflight: Evidence from biochemistry and densitometry. *Journal of Bone and Mineral Research,27*(9), 1896-1906. doi:10.1002/jbmr.1647

[4] Lacquaniti, F. (2017, October 04). ELaboratore Immagini TElevisive - Space 2 (ELITE-S2) - 10.04.17. Retrieved from https://www.nasa.gov/mission_pages/station/research/experiments/78.html

[5] Greenisen, M. (n.d.). Evaluation of the MK I Rowing Machine (DTO 653). Retrieved January 17, 2018, from https://lsda.jsc.nasa.gov/Experiment/exper/1748

[6] De Witt, J. K. (2017, May 17). Biomechanical Analysis of Treadmill Exercise on the International Space Station (Treadmill Kinematics) - 05.17.17. Retrieved from https://www.nasa.gov/mission_pages/station/research/experiments/819.html

[7] Downs, M. (2017, January 24). In-Flight Demonstration of the Miniature Exercise Device (MED-2). Retrieved from https://ntrs.nasa.gov/search.jsp?R=20170001374

[8] 2015 NASA Technology Roadmaps. Retrieved from https://www.nasa.gov/offices/oct/home/roadmaps/index.html

[9] Petersen, N., Jaekel, P., Rosenberger, A., Weber, et al. (2016). Exercise in space: the European Space Agency approach to in-flight exercise countermeasures for long-duration missions on ISS. *Extreme Physiology & Medicine,5*(1). doi:10.1186/s13728-016-0050-4

[10] Ploutz-Snyder, L., et al. (2018). Optimization of In-Flight Exercise Countermeasures - SPRINT. *2018 NASA Human Research Program Investigator's Workshop*.

[11] Taylor, G., & Smith, W. (1999). Extended Duration Orbiter Medical Project Final Report 1989–1995 (C. Sawin, Ed.). Retrieved from https://lsda.jsc.nasa.gov/books/ground/SP-1999-534.pdf

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[12] Lostroscio, K. (2018). Kinematic Information from MED-2 Parabolic Flight Campaign. *2018 NASA Human Research Program Investigator's Workshop*.

[13]Newby, N., et al. (2018). MED-2 ISS Flight Study. *2018 NASA Human Research Program Investigator's Workshop*.

[14] Eid, R. M. (2018, January 10). Cycle Ergometer with Vibration Isolation and Stabilization (CEVIS) System (CEVIS) - 01.10.18. Retrieved from https://www.nasa.gov/mission_pages/station/research/experiments/841.html

[15] Murray, M. (2017, September 06). Treadmill with Vibration Isolation and Stabilization System (TVIS) - 09.06.17. Retrieved from https://www.nasa.gov/mission_pages/station/research/experiments/976.html

[16] Burkhart, C. W. (2018, February 28). Advanced Resistive Exercise Device (ARED) - 02.28.18. Retrieved from https://www.nasa.gov/mission_pages/station/research/experiments/1001.html

[17] Funk, J. (2018). ATLAS (Advanced Twin Lifting and Aerobic System) Development Overview. *2018 NASA Human Research Program Investigator's Workshop*.

[18] Moore, C. (2017, December 06). Miniature Exercise Device (MED-2) - 12.06.17. Retrieved from https://www.nasa.gov/mission_pages/station/research/experiments/862.html

[19] McPherson, K., Hrovat, K., Kelly, E., & Keller, J. (2016, July 06). A Researcher's Guide to: Acceleration Environment. Retrieved from https://www.nasa.gov/sites/default/files/atoms/files/acceleration-environment-iss-mini-book_detail-508c.pdf

[20] Niebuhr, J., & Hagen, H. (2011). Development of the Vibration Isolation System for the Advanced Resistive Exercise Device. *41st Aerospace Mechanisms Symposium*. Retrieved from https://ntrs.nasa.gov/search.jsp?R=20110024049

[21] Dali, S., Justine, M., Ahmad, H., & Othman, Z. (2013). Comparison of ground reaction force during different angle of squatting. *Journal of Human Sport and Exercise,8*(3), 778-787. doi:10.4100/jhse.2013.83.02

[22] Schoenfeld, B. J. (2010). Squatting Kinematics and Kinetics and Their Application to Exercise Performance. *Journal of Strength and Conditioning Research,24*(12), 3497-3506. doi:10.1519/jsc.0b013e3181bac2d7

[23] Buckeridge, E. (2013). *Biomechanical Asymmteries and Joint Loading In Elite Rowers*(Doctoral Thesis). Imperial College London. Retrieved from https://spiral.imperial.ac.uk/bitstream/10044/1/28699/1/Buckeridge-E-2014-PhD-Thesis.pdf

[24] Inman, D. J. (2014). *Engineering Vibration* (4th ed.). Boston: Pearson.

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[25] Moog. (2015, December). Motion Systems for a Wide Range of Payload Applications. Retrieved from http://www.moog.com/content/dam/moog/literature/ICD/Moog-Simulation-Motion_Systems-en.pdf

[26] Van den Bogert, A. J., Geijtenbeek, T., Even-Zohar, O., Steenbrink, F., & Hardin, E. C. (2013). A real-time system for biomechanical analysis of human movement and muscle function. *Medical & Biological Engineering & Computing,51*(10), 1069-1077. doi:10.1007/s11517-013-1076-z

[27] National Aeronautics and Space Administration. (1999, December). International Space Station Flight Crew Integration Standard, SSP 50005C, 3-1.

[28] Guilliams, M., Rapley, M., & Nahom, B. (2002, Jan 01). Resistive Exercise Description Document, JSC 29558.

[29] Vicon Motion Systems. (2018). Comparison of skeleton calibration operations - Nexus 2.5 Documentation. Retrieved from https://docs.vicon.com/display/Nexus25/Comparison of skeleton calibration operations

[30] Pipeline tools - Nexus 2.5 Documentation. (2018). Retrieved from https://docs.vicon.com/display/Nexus25/Pipeline tools

[31] Newby, N., Caldwell, E., Sibonga, J., & Ploutz-Snyder, L. (2014, January 01). ISS Squat and Deadlift Kinematics on the Advanced Resistive Exercise Device. Retrieved from https://ntrs.nasa.gov/search.jsp?R=20140013188

[32] Zatsiorsky, V. M. (2002). *Kinetics of Human Motion*. Champaign, IL: Human Kinetics.

APPENDICES

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Appendix A: IRB Approval Letter

USF
UNIVERSITY OF SOUTH FLORIDA

RESEARCH INTEGRITY AND COMPLIANCE
Institutional Review Boards, FWA No. 00001669
12901 Bruce B. Downs Blvd., MDC035 ● Tampa, FL 33612-4799
(813) 974-5638 ● FAX (813) 974-7091

1/9/2018

Kaitlin Lostroscio
School of Physical Therapy & Rehabilitation Sciences

Tampa, FL 33620

RE: **Expedited Approval for Initial Review**
IRB#: Pro00032395
Title: Biomechanics for Enhancement & Verification of Countermeasure Analysis Tools for
        Human Exploration Missions

Study Approval Period: 1/8/2018 to 1/8/2019

Dear K. Lostroscio:

On 1/8/2018, the Institutional Review Board (IRB) reviewed and **APPROVED** the above
application and all documents contained within, including those outlined below.

Approved Item(s):
Protocol Document(s):
Protocol

Consent/Assent Document(s)*:
Adult Photo Release.pdf
Informed Consent.pdf

*Please use only the official IRB stamped informed consent/assent document(s) found under the
"Attachments" tab. Please note, these consent/assent documents are valid until the consent
document is amended and approved.

It was the determination of the IRB that your study qualified for expedited review which
includes activities that (1) present no more than minimal risk to human subjects, and (2) involve
only procedures listed in one or more of the categories outlined below. The IRB may review
research through the expedited review procedure authorized by 45CFR46.110 and 21 CFR
56.110. The research proposed in this study is categorized under the following expedited review
category:

(6) Collection of data from voice, video, digital, or image recordings made for research purposes.

(7) Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

As the principal investigator of this study, it is your responsibility to conduct this study in accordance with IRB policies and procedures and as approved by the IRB. Any changes to the approved research must be submitted to the IRB for review and approval via an amendment. Additionally, all unanticipated problems must be reported to the USF IRB within five (5) calendar days.

We appreciate your dedication to the ethical conduct of human subject research at the University of South Florida and your continued commitment to human research protections. If you have any questions regarding this matter, please call 813-974-5638.

Sincerely,

E. Verena Jorgensen, M.D., Chairperson
USF Institutional Review Board

Appendix B: Sample Questionnaire

Study on Exercise with Dynamic Platform: Questionnaire

Subject Designation: _____   Date: _____

Age: _____

Questions related to exercise experience:

1. How many times a week do you typically exercise (past 1-2 months)?

2. Please describe your exercise regime (types of exercises, time/reps, weight, etc.). Include both resistive and aerobic exercise:

3. Where/ when did you learn how to do squats and rowing?

4. How were the squats and rowing exercises different than how you are used to completing them?

5. Are there other sports, training, or exercise activities you engage in?

---

www.manaraa.com

Questions relating to the study:
For each question, please also provide additional information/ clarifications as needed in the "Explanation" area

THE FOLLOWING QUESTIONS FOR SQUATS

6. I was able to complete a squat as instructed while the platform was moving (circle one):

| Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |

Please Explain:

7. I found it difficult to complete the squats while the platform was moving (circle one):

| Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |

Please describe the nature of any difficulties you had:

8. I was able to *adapt to*/*match*/*sync with* the platform motion during squats (circle one):

| Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |

Please Explain:

9. I felt that completing the squat exercises while the platform was moving was comfortable:

| Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |

Please specify the conditions (speeds, motions, etc.) which were noticeably comfortable and uncomfortable. You can compare to your baseline speed if you like and reference the slow, medium, and fast rates tested with vertical platform motion:
Comfortable:

Uncomfortable:

THE FOLLOWING QUESTIONS FOR ROWS

10. I was able to complete a row as instructed while the platform was moving (circle one):

| Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |

Please Explain:

11. I found it difficult to complete the rows while the platform was moving (circle one):

| Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |

Please describe the nature of any difficulties you had:

12. I was able to *adapt to*/*match*/*sync with* the platform motion during rowing (circle one):

| Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |

Please Explain:

13. I felt that completing the row exercises while the platform was moving was comfortable:

| Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |

Please specify the conditions (speeds, motions, etc.) which were noticeably comfortable and uncomfortable. You can compare to your baseline speed if you like and reference the slow, medium, and fast rates tested with vertical platform motion and the very small, small, medium, and large angles of platform tilt tested:

Comfortable:

Uncomfortable:

General Questions:

14. Did you experience any motion sickness?

    Yes   No   Not Sure

    If so, when?

15. Did you use any senses other than "feel" (such as visual or auditory) to balance and compete the exercises?

    Yes   No   Not Sure

    If so, please specify any visual, auditory, or other cues you used from the environment:

16. Please provide any other feedback or relevant information you would like to provide:

Appendix C: Extended Responses from Questionnaire

Table A.1: Questionnaire Responses

Question	Subject	Response
1	1	5 times a week
	2	5x/week
	3	3
	4	7 days/week
2	1	Weightlifting including squats, deadlifts, chest presses, dumbbell curls
	2	Weights, workout classes, running 20mi/wk
	3	running 3x, push up 2x, sit up 2x, squats
	4	Aerobic: 0.5 mile reps x20-30 3 days/week, 20 min variable med ball slams, aerobic lunges/squats, etc. Resistance: upper/lower body compound lifts including: squats, bench press, snatch, clean, military press, etc. on average 4 sets of 8-12 reps of 60-80%. 1 rep maximum.
3	1	Squatting I learned about a year ago when I recreationally weightlifted in high school. Rowing I have known about for 7 years and have attempted on a handful of occasions
	2	with a trainer, gym
	3	gym, team sports
	4	Workout programs as a young middle/elementary school athlete
4	1	Squatting was done with a narrower stance than I normally take since I tend to sumo squat. The rowing was done vertically whereas I am used to using an ergometer.
	2	squats were normal, rowing was standing not machine
	3	squats: usually do with arms out, rowing: on machine - feels different w/out machine
	4	Slightly different form.
5	1	Water polo
	2	running
	3	swimming - summer/spring
	4	Basketball, football, swimming, surfing, skating, etc.
6	1	Agree, I could do the squats when the platform moved at a pace closest to my natural pace
	2	Agree
	3	Strongly Agree
	4	Strongly Agree
7	1	Agree, Even though I could complete the squats, I had to focus harder than normal to make sure I maintained balance and form while keeping up with the pace
	2	Disagree
	3	Disagree
	4	Strongly Disagree

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8	1	Neutral, During the speeds that matched my own I could match the platform, however when it was really slow or really fast I had a harder time and would often match but then lose the pace later.
	2	Agree
	3	Neutral, sometimes yes, sometimes no
	4	Strongly Agree
9	1	Neutral, Comfortable: Speed matching my baseline as well as those slightly faster, Uncomfortable: very slow speeds and very fast speeds
	2	Agree
	3	Agree, Uncomfortable: Slow - hard to match; hard on muscles/back
	4	Strongly Agree, Comfortable: All, Uncomfortable: None
10	1	Agree, I could perform the movement yet not as easily as when still
	2	Agree
	3	Agree
	4	Strongly Agree
11	1	Strongly Agree, I had trouble maintaining my balance and form. I could tell I was compromising form to keep up with pace or the angle.
	2	Disagree
	3	Disagree
	4	Strongly Disagree
12	1	Neutral, Sometimes I would match then lose the pace in the next row
	2	Agree
	3	Neutral, sometimes hard to match, sometimes easy to match
	4	Strongly Agree
13	1	Disagree, Comfortable: The speed of my baseline was easiest however I wouldn't say it was "easy". Slower speeds were better than faster to match, Uncomfortable: Most of the speeds off my baseline were hard to match as well and I would get on pace and then go right back off
	2	Neutral, Uncomfortable: out of sync tilt
	3	Agree, Comfortable: mostly, Uncomfortable: - sometimes - slow - back
	4	Strongly Agree, Comfortable: All, Uncomfortable: None
14	1	Yes, Only a little when the platform started to tilt at large degrees
	2	No
	3	No
	4	No
15	1	Yes, I relied heavily on auditory aid as well as watching the platform move relative to the concrete
	2	Yes: auditory
	3	Yes, auditory, visual: sometimes marker on platform
	4	Yes, sounds of platform moving

Appendix D: Estimated Force Frequency Matching

Table A.2: Estimated Frequency of Exercise

Subject	Trial	Avg.Frequency (Hz)	FPks	PPks
1	3	0.346	18	9
	4	0.25	25	5
	5	0.342	19	10
	6	0.608	22	11
	7	0.426	20	10
	8	0.161	10	0
	9	0.187	12	4
	10	0.344	20	10
	11	0.571	21	11
	12	0.414	21	11
	13	0.412	21	10
	14	0.372	19	10
	15	0.414	21	10
	16	0.401	22	11
	17	0.503	15	12
	18	0.306	8	9
	19	0.313	9	8
2	3	0.467	20	0
	4	0.484	37	4
	5	0.43	25	10
	6	0.61	25	12
	7	0.596	30	11
	8	0.426	16	100
	9	0.568	57	5
	10	0.387	25	11
	11	0.581	24	12
	12	0.56	22	11
	13	0.497	19	11
	14	0.586	23	12
	15	0.357	4	7
	16	0.577	22	11

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Table A.2 (Continued)

	3	0.552	19	0
	4	0.628	59	5
	5	0.524	28	10
	6	0.614	23	11
	7	0.542	19	9
	8	0.262	10	16
	9	0.619	54	5
	10	0.405	22	10
3	11	0.371	17	14
	12	0.283	14	13
	13	0.339	14	11
	14	0.363	12	9
	15	0.431	18	11
	16	0.423	19	13
	17	0.581	19	9
	18	0.381	15	10
	19	0.469	17	9
	3	0.54	18	0
	4	0.108	10	5
	5	0.284	15	9
	6	0.635	23	11
	7	0.641	19	10
	8	0.301	11	15
	9	0.149	12	4
	10	0.468	27	11
4	11	0.383	13	10
	12	0.306	10	10
	13	0.423	17	13
	14	0.483	17	10
	15	0.475	19	11
	16	0.375	15	11
	17	0.333	8	7
	18	0.298	10	10
	19	0.294	10	9

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Appendix E: MATLAB Script for Force Analysis

```matlab
%% Force Plate & Platform Analysis
% Kaitlin Lostroscio 2018
% Code for each individual Subject, trial batch processing

% Acknowledgments:
% Process for graphing adapted from: "Creating high-quality graphics in
% MATLAB for papers and presentations", Tamara G. Kolda, Sandia National
% Laboratories and David F. Gleich, Purdue University. April 2013.
% https://dgleich.wordpress.com/2013/06/04/creating-high-quality-
% graphics-in-matlab-for-papers-and-presentations/

clear all
close all
clc

% Set Inputs
SubjectNumber = 4;

% Figure Size
w = 3.3; % width in inches
h = 3.3; % height in inches

% Subject Specific Issues
if SubjectNumber==1
    istart=3; %start at baseline
    iend = 19;
elseif SubjectNumber==2
    istart=1;
    iend=16;
elseif SubjectNumber==3
    istart=1;
    iend=20;
elseif SubjectNumber==4
    istart=3; %start at baseline
    iend=19;
else
    istart=1;
    iend=19;
end

% Create Digital Butterworth Filter
fc = 6; % Cutoff Frequency (Hz)
fs = 300; % Force Plate Sampling Frequency (Hz)
%fs = length(XF0)/max(XF0) % Alternate method (to determine fs via data)

[b,a] = butter(3,fc/(fs/2)); %3rd order and normalized cutoff freq
figure(1)
freqz(b,a);

%% PROCESSING
SubjectNum = num2str(SubjectNumber);
```

```matlab
for i = istart:1:iend

% LOAD AND FILTER DATA
% Get Subject Specific Info for Baseline
%  Amplitude (m) & Frequency (Hz) (Squat & Row)
if SubjectNumber == 1
    baseamp = 0.0470;
    basefreqS = 0.4167;
    basefreqR = 0.4068;
elseif SubjectNumber == 2
    baseamp = 0.0355;
    basefreqS = 0.4460;
    basefreqR = 0.5750;
elseif SubjectNumber == 3
    baseamp = 0.0385;
    basefreqS = 0.4916;
    basefreqR = 0.5061;
elseif SubjectNumber == 4
    baseamp = 0.0475;
    basefreqS = 0.6711;
    basefreqR = 0.5695;
else
    error('Invalid Subject Number.')
end




% Get Trial Number Extension
if i < 10
    TrialNum = strcat('000',num2str(i));
else
    TrialNum = strcat('00',num2str(i));
end



% Get Trial Description
switch i
    case 1; Trial = 'Static T-Pose';
    case 2; Trial = 'ROM Test';
    case 3; Trial = 'Squat: Baseline (static)';
    case 4; Trial = strcat('Squat: 0.10 Hz, ',num2str(baseamp),' m ');
    case 5; Trial = strcat('Squat: 0.35 Hz, ',num2str(baseamp),' m ');
    case 6; Trial = strcat('Squat: 0.60 Hz, ',num2str(baseamp),' m ');
    case 7; Trial = strcat('Squat: ',num2str(basefreqS),' Hz, ', ...
            num2str(baseamp),' m ');
    case 8; Trial = 'Row: Baseline (static)';
    case 9; Trial = strcat('Row: 0.10 Hz, ',num2str(baseamp),' m ');
    case 10; Trial = strcat('Row: 0.35 Hz, ',num2str(baseamp),' m ');
    case 11; Trial = strcat('Row: 0.60 Hz, ',num2str(baseamp),' m ');
    case 12; Trial = strcat('Row: ',num2str(basefreqR),' Hz, ', ...
            num2str(baseamp),' m ');
    case 13; Trial = strcat('Row: ',num2str(basefreqR),' Hz, ', ...
            num2str(baseamp),' m, 0.5 deg ');
    case 14; Trial = strcat('Row: ',num2str(basefreqR),' Hz, ', ...
            num2str(baseamp),' m, 1 deg ');
    case 15; Trial = strcat('Row: ',num2str(basefreqR),' Hz, ', ...
```

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```matlab
                num2str(baseamp),' m, 2 deg ');
        case 16; Trial = strcat('Row: ',num2str(basefreqR),' Hz, ', ...
                num2str(baseamp),' m, 3 deg ');
        case 17; Trial = strcat('Row: ',num2str(basefreqR),' Hz, ', ...
                num2str(baseamp),' m, 4 deg ');
        case 18; Trial = strcat('Row: ',num2str(basefreqR),' Hz, ', ...
                num2str(baseamp),' m, 5 deg ');
        case 19; Trial = strcat('Row: ',num2str(basefreqR),' Hz, ', ...
                num2str(baseamp),' m, 6 deg ');
        otherwise; Trial = TrialNum;
end

% Directories
TopLevel = 'D:\NSTRF\Thesis\CAREN\NSTRF\';
FPLevel = '\ForcePlates\';
PlatformLevel = '\Platform\';

% Load Force Plate Data
ForcePlateLocate = strcat(TopLevel,'Subject',SubjectNum,FPLevel);
ForcePlateTrial = strcat('S',SubjectNum,'_','ForcePlates',TrialNum,'.txt');
ForcePlateFile = strcat(ForcePlateLocate,ForcePlateTrial);

ForcePlate = tdfread(ForcePlateFile);

% Load Platform Data
PlatformLocate = strcat(TopLevel,'Subject',SubjectNum,PlatformLevel);
PlatformTrial = strcat('S',SubjectNum,'_','Platform',TrialNum,'.txt');
PlatformFile = strcat(PlatformLocate,PlatformTrial);

Platform = tdfread(PlatformFile);

% Extract needed column vectors from structs
% Force Plates
XF = ForcePlate.Time;
ForX1 = ForcePlate.FP1_ForX;
ForY1 = ForcePlate.FP1_ForY;
ForZ1 = ForcePlate.FP1_ForZ;
ForX2 = ForcePlate.FP2_ForX;
ForY2 = ForcePlate.FP2_ForY;
ForZ2 = ForcePlate.FP2_ForZ;

% Platform
XP = Platform.Time;
PosX = Platform.PosX;
PosY = Platform.PosY;
PosZ = Platform.PosZ;
RotX = Platform.RotX;
RotY = Platform.RotY;
RotZ = Platform.RotZ;


% Filter Force Plates:
%  Low pass Butterworth (tf coeff a & b created at top)
ForY1_filt = filtfilt(b,a,ForY1); % zero-phase digital filter
ForY2_filt = filtfilt(b,a,ForY2); % zero-phase digital filter
```

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```matlab
% Find Resultant Force in Y Component
%  Note: Same whether add then filter or filter then add
FYR = ForY1_filt + ForY2_filt;



% Parse Range of Data to Activate-Stop Times
%  Checking for event marker increments

% Platform
ActP = Platform.Motion_Activated_Inc;
StopP = Platform.Motion_Stopped_Inc;
initAP = ActP(1);
initSP = StopP(1);
p = 1;

for m = 1:1:length(PosY)
    if (ActP(m) == initAP+1) && (StopP(m) < initSP+1);
        PP(p) = PosY(m); % Parsed Platform data
        PTP(p) = XP(m); % Parsed Time for Platform
        p = p+1;
    elseif (initAP==ActP(length(PosY))) && (initSP==StopP(length(PosY)));
        % Baseline trial, platform static
        PP = PosY;
        PTP = XP;
    end
end

% Force Plates
ActF = ForcePlate.Motion_Activated_Inc;
StopF = ForcePlate.Motion_Stopped_Inc;
initAF = ActF(1);
initSF = StopF(1);
q = 1;

% Quick check for Unmatching Data
if initAF ~= initAP
    error('Unmatched Data. Check for mislabelled files.')
    % If a trial was redone due to an operational issue, the Platform and
    % Force Plate files were deleted manually so that the file append value
    % would match the trial number. If a file was not deleted, this could
    % occur.
end

for n = 1:1:length(FYR)
    if (ActF(n) == initAF+1) && (StopF(n) < initSF+1)
        PF(q) = FYR(n); % Parsed Force Plate data
        PTF(q) = XF(n); % Parsed Time for Force Plates
        q = q+1;
    elseif (initAF==ActF(length(FYR))) && (initSF==StopF(length(FYR)));
        % Baseline trial
        PF = FYR;
        PTF = XF;
    end
end
```

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```matlab
% FORCE MAGNITUDE ANALYSIS
% Find Peaks and Troughs

% Find peak magnitudes
[maxF,maxlocs] = findpeaks(PF,'MinPeakProminence',50);
    if length(maxF) <= 1 % if no more than 1 peak identified
        [maxF,maxlocs] = findpeaks(PF); %remove prominence
    end
PFinv = 1.01*max(PF) - PF; % (Need troughs to be peaks for 'findpeaks')
% Find time of troughs
[min_temp,minlocs] = findpeaks(PFinv,'MinPeakProminence',50);
    if length(min_temp) <= 1 % if no more than 1 peak identified
        [min_temp,minlocs] = findpeaks(PFinv); %remove prominence
    end
% Find trough magnitudes
minF = PF(minlocs);

% Find Range of Peak to Trough (each cycle)
for k=1:1:min(length(maxF),length(minF))
    Force_Range = maxF(k) - minF(k);
end
% Find average range
F_RangeAvg = sum(Force_Range)/length(Force_Range);
% Find average max force
F_MaxAvg = sum(maxF)/length(maxF);

%plot(PTF,PF) % For reference during checking

% Write to File
fID=fopen('D:\NSTRF\Thesis\Matlab_Excel\Tables\ForceRanges.txt','a+');
fprintf(fID,'%6s %6s %6s %6s\r\n','Subject','Trial','Avg.ForceRange', ...
    'Avg.ForceMax');
fprintf(fID,'%1.0f %2.0f %2.3f %2.0f \r\n',SubjectNumber,i, ...
    F_RangeAvg,F_MaxAvg);
fclose(fID);


% FREQUENCY MATCHING ANALYSIS
% Normalize data (from the parsed, filtered data)
PY_norm = (PP - min(PP))/(max(PP)-min(PP));
FY_norm = (PF - min(PF))/(max(PF)-min(PF));

% Time Advance
TP0 = PTP - PTP(1); % shifting time to zero start
TF0 = PTF - PTF(1);

% Plot the normalized data
figure(3)
fpos = get(gcf, 'Position');
set(gcf, 'Position', [fpos(1) fpos(2) w*100, h*100]); % Set size
a1=area(TP0,PY_norm,'FaceColor',[0.8 0.8 0.8]);
hold on
p1=plot(TP0,PY_norm,'Color',[0.5 0.5 0.5],'LineStyle','-','LineWidth',1);
hold on
```

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```matlab
p2=plot(TF0,FY_norm,'Color',[0 0.4470 0.7410],'LineWidth',1);
axis([0 max(TP0) 0 1]);
title({'Normalized Platform & Force Data',strcat('S',SubjectNum,'- ', ...
    Trial)},'FontSize',12,'FontName','times')
legend([p1 p2],{'Platform Y','Force Y'},'Location','SouthOutside', ...
    'Orientation','horizontal')
xlabel('Time (sec)','FontSize',12,'FontName','times')
ylabel('Normalized Force and Position','FontSize',12,'FontName','times')
set(gca,'FontName','times','FontSize',12,'LineWidth', 1); % Set axes props
set(gca, 'Layer', 'top');
set(gca,'XTick',[min(TF0):5:max(TF0)])
set(gca,'YTick',[0:0.1:1])
% Preserve Size
set(gcf,'InvertHardcopy','on');
set(gcf,'PaperUnits', 'inches');
papersize = get(gcf, 'PaperSize');
left = (papersize(1)- w)/2;
bottom = (papersize(2)- h)/2;
myfiguresize = [left, bottom, w, h];
set(gcf,'PaperPosition', myfiguresize);
% Save to File
print(strcat('D:\NSTRF\Thesis\Matlab_Excel\Plots\NormalizedData_S', ...
    SubjectNum,'T',TrialNum),'-dpng','-r300');


% Estimating Frequency of Force Data from Peaks
% Find all peaks for Force (with Peak Prominence - min Y dist both slopes)
[pks,locs] = findpeaks(FY_norm,'MinPeakProminence',0.2);
NumPeaks = length(pks);
if NumPeaks <= 1 % if no more than 1 peak identified
    [pks,locs] = findpeaks(FY_norm); %remove prominence
end
% Platform Peaks for checking
[Ppks,Plocs] = findpeaks(PY_norm);
NPP = length(Ppks);

% Find times of those Force peaks
for r = 1:1:length(locs)
    t(r) = TF0(locs(r));
end

% Find the period (time between peaks)
for u = 1:1:length(t)-1
    T(u) = t(u+1)-t(u);
end

% Find the average period
T_avg = sum(T)/length(T);
% Convert to Frequency & account for more than 1 peak per cycle
F_avg = 1/(T_avg*2); % There are ~2 peaks in a cycle

% Write to File
fID=fopen('D:\NSTRF\Thesis\Matlab_Excel\Tables\ForceFrequencies.txt','a+');
fprintf(fID,'%6s %6s %6s %6s %6s\r\n','Subject','Trial', ...
    'Avg.Frequency(Hz)','FPks','PPks');
fprintf(fID,'%1.0f %2.0f %2.3f %2.0f %2.0f\r\n',SubjectNumber,i, ...
```

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```matlab
    F_avg,NumPeaks,NPP);
fclose(fID);

% Clear figures
clf
close all
clearvars -except SubjectNumber SubjectNum a b h w
end

%% Filtered Force Baseline Comparisons
% Squat: 3&7, Row: 8&12

SubjectNum = num2str(SubjectNumber);

% Figure Size
w2 = 6% width in inches
h2 = 4% height in inches

hold on
for i = [3,7,8,12]

% LOAD AND FILTER DATA
% Get Subject Specific Info for Baseline
%  Amplitude (m) & Frequency (Hz) (Squat & Row)
if SubjectNumber == 1
    baseamp = 0.0470;
    basefreqS = 0.4167;
    basefreqR = 0.4068;
elseif SubjectNumber == 2
    baseamp = 0.0355;
    basefreqS = 0.4460;
    basefreqR = 0.5750;
elseif SubjectNumber == 3
    baseamp = 0.0385;
    basefreqS = 0.4916;
    basefreqR = 0.5061;
elseif SubjectNumber == 4
    baseamp = 0.0475;
    basefreqS = 0.6711;
    basefreqR = 0.5695;
else
    error('Invalid Subject Number.')
end




% Get Trial Number Extension
if i < 10
    TrialNum = strcat('000',num2str(i));
else
    TrialNum = strcat('00',num2str(i));
end


% Get Trial Description
```

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```matlab
    switch i
        case 3; Trial = 'Squat: Baseline (static)';
        case 7; Trial = strcat('Squat: ',num2str(basefreqS),' Hz, ', ...
                num2str(baseamp),' m ');
        case 8; Trial = 'Row: Baseline (static)';
        case 12; Trial = strcat('Row: ',num2str(basefreqR),' Hz, ', ...
                 num2str(baseamp),' m ');
        otherwise; Trial = TrialNum;
    end

    % Directories
    TopLevel = 'D:\NSTRF\Thesis\CAREN\NSTRF\';
    FPLevel = '\ForcePlates\';

    % Load Force Plate Data
    ForcePlateLocate = strcat(TopLevel,'Subject',SubjectNum,FPLevel);
    ForcePlateTrial = strcat('S',SubjectNum,'_','ForcePlates',TrialNum,'.txt');
    ForcePlateFile = strcat(ForcePlateLocate,ForcePlateTrial);

    ForcePlate = tdfread(ForcePlateFile);

    % Extract needed column vectors from structs
    % Force Plates
    XF = ForcePlate.Time;
    XF0 = XF - XF(1);
    ForX1 = ForcePlate.FP1_ForX;
    ForY1 = ForcePlate.FP1_ForY;
    ForZ1 = ForcePlate.FP1_ForZ;
    ForX2 = ForcePlate.FP2_ForX;
    ForY2 = ForcePlate.FP2_ForY;
    ForZ2 = ForcePlate.FP2_ForZ;

    % Filter Force Plates:
    %  Low pass Butterworth (tf coeff a & b created at top)
    ForY1_filt = filtfilt(b,a,ForY1); % zero-phase digital filter
    ForY2_filt = filtfilt(b,a,ForY2); % zero-phase digital filter

    % Find Resultant Force in Y Component
    %  Note: Same whether add then filter or filter then add
    FYR = ForY1_filt + ForY2_filt;

    % Parse Range of Data to Activate-Stop Times
    %  Checking for event marker increments

    % Force Plates
    ActF = ForcePlate.Motion_Activated_Inc;
    StopF = ForcePlate.Motion_Stopped_Inc;
    initAF = ActF(1);
    initSF = StopF(1);
    q = 1;
```

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```matlab
for n = 1:1:length(FYR)
    if (ActF(n) == initAF+1) && (StopF(n) < initSF+1)
        PF(q) = FYR(n); % Parsed Force Plate data
        PTF(q) = XF(n); % Parsed Time for Force Plates
        q = q+1;
    elseif (initAF==ActF(length(FYR))) && (initSF==StopF(length(FYR)));
        % Baseline trial
        PF = FYR;
        PTF = XF;
    end
end

% Start at second definitive peak, end at last
[pks,locs] = findpeaks(PF,'MinPeakProminence',100);
% PF_trim = PF(locs(2):max(locs));
% PTF_trim = PTF(locs(2):max(locs));
e = length(locs)-2 % Correction for miscellaneous data wrapping
PF_trim = PF(locs(2):locs(e));
PTF_trim = PTF(locs(2):locs(e));

% Time Advance
TF0 = PTF_trim - PTF_trim(1); % shifting time to zero start



% Plotting Baseline (Static) vs Dynamic Platform

% Squats
if i == 3 | i==7
   if i==3
       c = [0.2 0.3 1];
   elseif i==7
       c = [0.2 0.6 1];
   end
    figure(4)
    fpos = get(gcf, 'Position');
    set(gcf, 'Position', [fpos(1) fpos(2) w2*100, h2*100]); % Set size
    plot(TF0(1:end-1),PF_trim(1:end-1),'Color',c,'LineStyle','-', ...
        'LineWidth',1.5)
    hold on
    axis([0 inf -inf inf])%([0 12 -inf inf])%S4
    title(strcat('Squats: Baseline Static & Dynamic (','S',SubjectNum, ...
    ')'),'FontSize',12,'FontName','times')
    legend('Static','Dynamic','Location','SouthOutside', ...
    'Orientation','horizontal')
    xlabel('Time (sec)','FontSize',12,'FontName','times')
    ylabel('Force (N)','FontSize',12,'FontName','times')
    set(gca,'FontName','times','FontSize',12,'LineWidth', 1);
    set(gca, 'Layer', 'top');
    set(gca,'XTick',[0:2:max(TF0)])
    % Preserve Size
    set(gcf,'InvertHardcopy','on');
    set(gcf,'PaperUnits', 'inches');
    papersize = get(gcf, 'PaperSize');
```

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```matlab
        left = (papersize(1)- w2)/2;
        bottom = (papersize(2)- h2)/2;
        myfiguresize = [left, bottom, w2, h2];
        set(gcf,'PaperPosition', myfiguresize);
        % Save to File
        print(strcat('D:\NSTRF\Thesis\Matlab_Excel\Plots\BaselineForce_S', ...
            SubjectNum,'T3-7'),'-dpng','-r300');


        if i ==3
        % Plotting Static Baseline Only
        figure(5)
        fpos = get(gcf, 'Position');
        set(gcf, 'Position', [fpos(1) fpos(2) w2*100, h2*100]); % Set size
        plot(XF0,FYR,'Color',c,'LineStyle','-','LineWidth',1.5)
        axis([0 inf -inf inf])%([0 12 -inf inf])%S4
        title(strcat('Squats: Static Baseline (','S',SubjectNum, ...
        ')'),'FontSize',12,'FontName','times')
        legend('Static','Location','SouthOutside', ...
        'Orientation','horizontal')
        xlabel('Time (sec)','FontSize',12,'FontName','times')
        ylabel('Force (N)','FontSize',12,'FontName','times')
        set(gca,'FontName','times','FontSize',12,'LineWidth', 1);
        set(gca, 'Layer', 'top');
        set(gca,'XTick',[0:2:max(XF0)])
        % Preserve Size
        set(gcf,'InvertHardcopy','on');
        set(gcf,'PaperUnits', 'inches');
        papersize = get(gcf, 'PaperSize');
        left = (papersize(1)- w2)/2;
        bottom = (papersize(2)- h2)/2;
        myfiguresize = [left, bottom, w2, h2];
        set(gcf,'PaperPosition', myfiguresize);
        % Save to File
        print(strcat('D:\NSTRF\Thesis\Matlab_Excel\Plots\BaselineForce_S', ...
            SubjectNum,'T3'),'-dpng','-r300');
        end
    end


% Rows
if i == 8 | i==12
   if i==8
       c = [0.2 0.3 1];
   elseif i==12
       c = [0.2 0.6 1];
   end
    figure(6)
    fpos = get(gcf, 'Position');
    set(gcf, 'Position', [fpos(1) fpos(2) 6*100, 4.5*100]); % Set size
    plot(TF0,PF_trim,'Color',c,'LineStyle','-','LineWidth',1.5)
    hold on
    axis([0 inf -inf inf])%([0 13 -inf inf])%S4
    title(strcat('Rows: Baseline Static & Dynamic (','S',SubjectNum, ...
    ')'),'FontSize',12,'FontName','times')
    legend('Static','Dynamic','Location','SouthOutside', ...
```

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```matlab
    'Orientation','horizontal')
    xlabel('Time (sec)','FontSize',12,'FontName','times')
    ylabel('Force (N)','FontSize',12,'FontName','times')
    set(gca,'FontName','times','FontSize',12,'LineWidth', 1);
    set(gca, 'Layer', 'top');
    set(gca,'XTick',[0:2:max(TF0)])
    % Preserve Size
    set(gcf,'InvertHardcopy','on');
    set(gcf,'PaperUnits', 'inches');
    papersize = get(gcf, 'PaperSize');
    left = (papersize(1)- w2)/2;
    bottom = (papersize(2)- h2)/2;
    myfiguresize = [left, bottom, w2, h2];
    set(gcf,'PaperPosition', myfiguresize);
    % Save to File
    print(strcat('D:\NSTRF\Thesis\Matlab_Excel\Plots\BaselineForce_S', ...
        SubjectNum,'T8-12'),'-dpng','-r300');

    if i ==8
    figure(7)
    fpos = get(gcf, 'Position');
    set(gcf, 'Position', [fpos(1) fpos(2) 6*100, 4.5*100]); % Set size
    plot(XF0,FYR,'Color',c,'LineStyle','-','LineWidth',1.5)
    axis([0 inf -inf inf])%([0 13 -inf inf])%S4
    title(strcat('Rows: Dynamic Baseline (','S',SubjectNum, ...
    ')'),'FontSize',12,'FontName','times')
    legend('Static','Location','SouthOutside', ...
    'Orientation','horizontal')
    xlabel('Time (sec)','FontSize',12,'FontName','times')
    ylabel('Force (N)','FontSize',12,'FontName','times')
    set(gca,'FontName','times','FontSize',12,'LineWidth', 1);
    set(gca, 'Layer', 'top');
    set(gca,'XTick',[0:2:max(XF0)])
    % Preserve Size
    set(gcf,'InvertHardcopy','on');
    set(gcf,'PaperUnits', 'inches');
    papersize = get(gcf, 'PaperSize');
    left = (papersize(1)- w2)/2;
    bottom = (papersize(2)- h2)/2;
    myfiguresize = [left, bottom, w2, h2];
    set(gcf,'PaperPosition', myfiguresize);
    % Save to File
    print(strcat('D:\NSTRF\Thesis\Matlab_Excel\Plots\BaselineForce_S', ...
        SubjectNum,'T8'),'-dpng','-r300');
    end
end


end
hold off

% Clear figures
clf
close all
```

Appendix F: MATLAB Script for Motion Capture Analysis

```
%% Motion Capture Analysis
% Kaitlin Lostroscio 2018
% Code for each individual Subject, trial batch processing

close all
clear all
clf
clc

% Subject Number
SubjectNumber = 1;

% Side of Body (Left or Right Knee)
    % ='L' for Left, ='R' for Right
Side = 'L';


%% Average Knee Angle Baseline Comparisons
% Squat: 3&7, Row: 8&12

SubjectNum = num2str(SubjectNumber);

% Record Rate
fs = 100; %fps

% Figure Size
w2 = 3.25;% width in inches
h2 = 4;% height in inches


hold on
for i = [3,7,8,12]

% Set appropriate graph axis bounds
switch SubjectNumber
    case 1;
        switch i
            case{3,7};ax1 = 0;ax2 = 20;ay1 = 46;ay2 = 162;
            case{8,12};ax1 = 0;ax2 = 20;ay1 = 57;ay2 = 162;
        end
    case 2;
        switch i
            case{3,7};ax1 = 0;ax2 = 20;ay1 = 46;ay2 = 166;
            case{8,12};ax1 = 0;ax2 = 18;ay1 = 51;ay2 = 166;
        end
    case 3;
        switch i
            case{3,7};ax1 = 0;ax2 = 17;ay1 = 73;ay2 = 173;
            case{8,12};ax1 = 0;ax2 = 20;ay1 = 95;ay2 = 182;
        end
    case 4;
        switch i
```

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```matlab
            case{3,7};ax1 = 0;ax2 = 16;ay1 = 40;ay2 = 180;
            case{8,12};ax1 = 0;ax2 = 14;ay1 = 50;ay2 = 168;
        end
end


% LOAD AND FILTER DATA
% Get Subject Specific Info for Baseline
%  Amplitude (m) & Frequency (Hz) (Squat & Row)
if SubjectNumber == 1
    baseamp = 0.0470;
    basefreqS = 0.4167;
    basefreqR = 0.4068;
elseif SubjectNumber == 2
    baseamp = 0.0355;
    basefreqS = 0.4460;
    basefreqR = 0.5750;
elseif SubjectNumber == 3
    baseamp = 0.0385;
    basefreqS = 0.4916;
    basefreqR = 0.5061;
elseif SubjectNumber == 4
    baseamp = 0.0475;
    basefreqS = 0.6711;
    basefreqR = 0.5695;
else
    error('Invalid Subject Number.')
end




% Get Trial Number Extension
if i < 10
    TrialNum = strcat('000',num2str(i));
else
    TrialNum = strcat('00',num2str(i));
end


% Get Trial Description
switch i
    case 3; Trial = 'Squat: Baseline (static)';
    case 7; Trial = strcat('Squat: ',num2str(basefreqS),' Hz, ', ...
            num2str(baseamp),' m ');
    case 8; Trial = 'Row: Baseline (static)';
    case 12; Trial = strcat('Row: ',num2str(basefreqR),' Hz, ', ...
             num2str(baseamp),' m ');
    otherwise; Trial = TrialNum;
end

% Directories
TopLevel = 'D:\NSTRF\Thesis\CAREN\NSTRF\';
MocapLevel = '\ASCII_Files\';

% Load Force Plate Data
```

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```matlab
MocapLocate = strcat(TopLevel,'Subject',SubjectNum,MocapLevel);
MocapTrial = strcat('S',SubjectNum,'_','Mocap',TrialNum,Side,'.txt');
MocapFile = strcat(MocapLocate,MocapTrial);


Mocap = tdfread(MocapFile);



% Extract needed column vectors from structs
% Mocap

Frame_Raw = Mocap.Frame;
KneeAngle_Raw = Mocap.KneeAngle;

% Convert Frames to Time
Time_temp = Frame_Raw/fs; % seconds
Time = Time_temp - Time_temp(1); % shift to zero

% Adjust for Knee Angle inbetween femur and tibia
% Mocap provided relative angle from tibia aligned vector to femur
% Need to subtract from 180 degrees
KneeAngle = 180 - KneeAngle_Raw; % Inner Knee Angle

%plot(Time,KneeAngle)



%  KNEE ANGLE ROM ANALYSIS

% Find Peaks and Troughs
% Find all peaks (with Peak Prominence - min Y dist both slopes)
[maxK,maxlocs] = findpeaks(KneeAngle,'MinPeakProminence',40);

% Find all troughs
% Shift troughs to be peaks
% (Need troughs to be peaks for 'findpeaks')
Kinv = 1.01*max(KneeAngle) - KneeAngle;
% Find time of troughs
[min_temp,minlocs] = findpeaks(Kinv,'MinPeakProminence',40);
% Find trough magnitudes
minK = KneeAngle(minlocs);

% Find Range of Peak to Trough (each cycle)
% Beginning with troughs (angle decrease) to define a cycle
for k=1:1:min(length(maxK),length(minK))
    KneeAngle_Range = abs(minK(k) - maxK(k)); %ROM of Knee during exercise
    SumKneeAng = maxK(k)+ minK(k);
end

% Find average range (ROM)
K_RangeAvg = sum(KneeAngle_Range)/length(KneeAngle_Range);

% Find Average of the midpoints (average) of each range
    % Find average of all elements in vector and divide by 2 to account for
    % element to element average
K_CenterLine = sum(SumKneeAng)/length(SumKneeAng)/2;
```

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```matlab
% Find Max and Mins associated with center range
    % (Placing Range Avg at CenterLine location)
K_RangeMax = K_CenterLine + (K_RangeAvg/2);
K_RangeMin = K_CenterLine - (K_RangeAvg/2);

% Find Average of Extrema for Comparison
    % (Different than element by element, cycle by cycle)
% Find average max
K_MaxAvg = sum(maxK)/length(maxK);
% Find average min
K_MinAvg = sum(minK)/length(minK);


%plot(PTF,PF) % For reference during checking

% Write to File
fID=fopen('D:\NSTRF\Thesis\Matlab_Excel\Tables\KneeAngleRanges.txt','a+');
fprintf(fID,'%6s %6s %6s %6s %6s %6s\r\n','Subject','Trial','Side', ...
    'Avg.KneeAngleRange','KneeAngleRangeMax','KneeAngleRangeMin');
fprintf(fID,'%1.0f %2.0f %s %3.5f %3.5f %3.5f\r\n',SubjectNumber,i, ...
    Side,K_RangeAvg,K_RangeMax,K_RangeMin);
fclose(fID);


% PLOTTING
% Start at first peak to help synchronization in Static vs Dynamic plots
KneeAngle0 = KneeAngle(maxlocs(1):length(KneeAngle),1);
tstart = Time(maxlocs(1));
Time_temp0 = Time(maxlocs(1):length(Time),1);
Time0 = Time_temp0 - tstart;

% Plotting Baseline (Static) vs Dynamic Platform
if Side == 'L'
   if i==3 | i==8
       c = [0.18 0.459 0.714];%[0.2 0.3 1];
   elseif i==7 | i==12
       c = [0.616 0.765 0.902];%[0.2 0.6 1];
   end
elseif Side == 'R'
   if i==3 | i==8
       c = [0.773 0.353 0.067];%[0.2 0.3 1];
   elseif i==7 | i==12
       c = [0.957 0.459 0.514];%[0.2 0.6 1];
   end
end

% Squats
if i ==3
    % Plotting Static Baseline Only
    figure(5)
    fpos = get(gcf, 'Position');
    set(gcf, 'Position', [fpos(1) fpos(2) w2*100, h2*100]); % Set size
    plot(Time0,KneeAngle0,'Color',c,'LineStyle','-','LineWidth',1.5)
    axis([ax1 ax2 ay1 ay2])
```

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```matlab
        title(strcat('Squats: Static Baseline (','S',SubjectNum, ...
        '-',Side,'\_Knee)'),'FontSize',12,'FontName','times')
        legend('Static','Location','SouthOutside', ...
        'Orientation','horizontal')
        xlabel('Time (sec)','FontSize',12,'FontName','times')
        ylabel({'Knee Angle (deg)', ...
            'Decreasing: Flexion, Increasing: Extension'}, ...
            'FontSize',12,'FontName','times')
        set(gca,'FontName','times','FontSize',12,'LineWidth', 1);
        set(gca, 'Layer', 'top');
        set(gca,'XTick',[0:2:max(Time)])
        % Preserve Size
        set(gcf,'InvertHardcopy','on');
        set(gcf,'PaperUnits', 'inches');
        papersize = get(gcf, 'PaperSize');
        left = (papersize(1)- w2)/2;
        bottom = (papersize(2)- h2)/2;
        myfiguresize = [left, bottom, w2, h2];
        set(gcf,'PaperPosition', myfiguresize);
        % Save to File
        print(strcat('D:\NSTRF\Thesis\Matlab_Excel\Plots\KneeAngle_S', ...
            SubjectNum,'T3',Side),'-dpng','-r300');
    end

    if i==7
        % Plotting Dynamic Baseline Only
        figure(4)
        fpos = get(gcf, 'Position');
        set(gcf, 'Position', [fpos(1) fpos(2) w2*100, h2*100]); % Set size
        plot(Time0,KneeAngle0,'Color',c,'LineStyle','-', ...
            'LineWidth',1.5)
        hold on
        axis([ax1 ax2 ay1 ay2])
        title(strcat('Squats: Dynamic Baseline (','S',SubjectNum, ...
        '-',Side,'\_Knee)'),'FontSize',12,'FontName','times')
        legend('Dynamic','Location','SouthOutside', ...
        'Orientation','horizontal')
        xlabel('Time (sec)','FontSize',12,'FontName','times')
        ylabel({'Knee Angle (deg)', ...
            'Decreasing: Flexion, Increasing: Extension'}, ...
            'FontSize',12,'FontName','times')
        set(gca,'FontName','times','FontSize',12,'LineWidth', 1);
        set(gca, 'Layer', 'top');
        set(gca,'XTick',[0:2:max(Time)])
        % Preserve Size
        set(gcf,'InvertHardcopy','on');
        set(gcf,'PaperUnits', 'inches');
        papersize = get(gcf, 'PaperSize');
        left = (papersize(1)- w2)/2;
        bottom = (papersize(2)- h2)/2;
        myfiguresize = [left, bottom, w2, h2];
        set(gcf,'PaperPosition', myfiguresize);
        % Save to File
        print(strcat('D:\NSTRF\Thesis\Matlab_Excel\Plots\KneeAngle_S', ...
            SubjectNum,'T7',Side),'-dpng','-r300');
    end
```

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```matlab
% Rows
if i ==8
    % Plotting Static Baseline Only
    figure(7)
    fpos = get(gcf, 'Position');
    set(gcf, 'Position', [fpos(1) fpos(2) w2*100, h2*100]); % Set size
    plot(Time0,KneeAngle0,'Color',c,'LineStyle','-','LineWidth',1.5)
    axis([ax1 ax2 ay1 ay2])
    title(strcat('Rows: Static Baseline (','S',SubjectNum, ...
    '-',Side,'\_Knee)'),'FontSize',12,'FontName','times')
    legend('Static','Location','SouthOutside', ...
    'Orientation','horizontal')
    xlabel('Time (sec)','FontSize',12,'FontName','times')
    ylabel({'Knee Angle (deg)', ...
        'Decreasing: Flexion, Increasing: Extension'}, ...
        'FontSize',12,'FontName','times')
    set(gca,'FontName','times','FontSize',12,'LineWidth', 1);
    set(gca, 'Layer', 'top');
    set(gca,'XTick',[0:2:max(Time)])
    % Preserve Size
    set(gcf,'InvertHardcopy','on');
    set(gcf,'PaperUnits', 'inches');
    papersize = get(gcf, 'PaperSize');
    left = (papersize(1)- w2)/2;
    bottom = (papersize(2)- h2)/2;
    myfiguresize = [left, bottom, w2, h2];
    set(gcf,'PaperPosition', myfiguresize);
    % Save to File
    print(strcat('D:\NSTRF\Thesis\Matlab_Excel\Plots\KneeAngle_S', ...
        SubjectNum,'T8',Side),'-dpng','-r300');
end

if i==12
    % Plotting Static Baseline Only
    figure(6)
    fpos = get(gcf, 'Position');
    set(gcf, 'Position', [fpos(1) fpos(2) w2*100, h2*100]); % Set size
    plot(Time0,KneeAngle0,'Color',c,'LineStyle','-','LineWidth',1.5)
    hold on
    axis([ax1 ax2 ay1 ay2])
    title(strcat('Rows: Dynamic Baseline (','S',SubjectNum, ...
    '-',Side,'\_Knee)'),'FontSize',12,'FontName','times')
    legend('Dynamic','Location','SouthOutside', ...
    'Orientation','horizontal')
    xlabel('Time (sec)','FontSize',12,'FontName','times')
    ylabel({'Knee Angle (deg)', ...
        'Decreasing: Flexion, Increasing: Extension'}, ...
        'FontSize',12,'FontName','times')
    set(gca,'FontName','times','FontSize',12,'LineWidth', 1);
    set(gca, 'Layer', 'top');
    set(gca,'XTick',[0:2:max(Time)])
    % Preserve Size
    set(gcf,'InvertHardcopy','on');
```

```matlab
        set(gcf,'PaperUnits', 'inches');
        papersize = get(gcf, 'PaperSize');
        left = (papersize(1)- w2)/2;
        bottom = (papersize(2)- h2)/2;
        myfiguresize = [left, bottom, w2, h2];
        set(gcf,'PaperPosition', myfiguresize);
        % Save to File
        print(strcat('D:\NSTRF\Thesis\Matlab_Excel\Plots\KneeAngle_S', ...
            SubjectNum,'T12',Side),'-dpng','-r300');
    end

    end

    hold off
```