STATIONARY EXERCISE BICYCLE INSTRUMENTATION AND VERIFICATION OF OPENSIM
PELVIC RESIDUAL LOADS IN SEATED CYCLING

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ABSTRACT

Stationary Exercise Bicycle Instrumentation and Verification of OpenSim Pelvic Residual Loads in Seated Cycling

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The study of cycling biomechanics typically requires measurement of pedal loads through force transducer instrumentation. However, analysis of seated cycling often necessitates the additional measurement of the loads exerted on the rider by the seat and handlebars. A stationary exercise bicycle was instrumented with two commercial six-axis force transducers at both the seat and handlebar locations via a custom designed mounting system. The system was tested by applying known forces and moments to the fixtures and proved capable of accurately measuring the loads. Additional data collected from cycling tests were compared to values from the literature to add supporting evidence to the validity of the system.

The instrumented stationary bicycle was further used to study the accuracy of modeling seated cycling in OpenSim. Five participants cycled at a moderate resistance level for three trials. Force and moment data were collected by seat, handlebar, and pedal load cells, while kinematic data were collected by an optical motion capture system. Participant data were analyzed with the OpenSim residual reduction algorithm (RRA) tool excluding seat and handlebar loads. The RRA pelvic residual was then compared to an experimentally determined handlebar and seat equivalent (HBSE) calculated from respective load cell data. Graphical comparisons of the RRA and HBSE results showed strong correlations in Anterior-Posterior (A-P) and Superior-Inferior (S-I) force directions and to a lesser degree, Medial-Lateral (M-L) force and S-I moment directions. M-L and A-P moment plots showed the least correlation between RRA and HBSE. Statistical comparisons showed RRA errors likely within 5.2% body weight (BW) for forces and 2.4% BW*height for moments. Considering the average participant height and weight of 167.7 cm and 63.6 kg, respectively, recommended error ranges for RRA are roughly $\pm 4.0\%$ BW for forces and $\pm 7.2\%$ BW*height for moments. This indicates that the OpenSim RRA tool can be used for cycling analysis.

Keywords: Cycling, Seat, Handlebar, Forces, Instrumentation, OpenSim, RRA

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Chapter 1

INTRODUCTION

1.1 Motivation

Cycling is a commonplace activity utilized for a wide range of purposes including recreation, exercise, transportation, and rehabilitation. Biomechanically, cycling offers strong lower body muscle engagement without the damaging impact loads associated with walking and running. These facts make cycling and its associated effects on the human body an important field of research. The Human Motion Biomechanics Laboratory (HMBL) at California Polytechnic State University, San Luis Obispo (Cal Poly) has conducted several previous studies on the effects of cycling loads on the knees of single leg amputees [1], persons having undergone ACL reconstruction surgery [2], and overweight and obese persons [3]. This previous research was conducted using a stationary exercise bicycle with pedals instrumented by past students [4]. Although much can be learned from examining pedal reactions alone, the absence of additional seat and handlebar reaction data limit the scope of future work and introduces unconfirmed assumptions into the analysis of past results. Further instrumentation of the bicycle seat and handlebars would increase the research capabilities of the HMBL and help to verify the conclusions of past studies.

1.2 Literature Review

Due to its popularity and ubiquity, cycling biomechanics has been the subject of much prior research. The earliest study of seat and handlebar loads was conducted by Soden and Adeyefa [5], who used 8mm film footage of a participant riding a typical road bicycle outdoors to calculate an average superior-inferior (S-I) seat force of 49% BW and an average handlebar S-I force of 4.5% BW. The first direct measurement of these loads was conducted by Bolourchi and Hull [6], who used strain gauges to capture handlebar S-I and anterior-posterior (A-P) forces as well as seat S-I forces and seat A-P and medial-lateral (M-L) moments. The results of this study showed the first plots of seat and handlebar load shapes. Data were collected from a participant riding a typical road bicycle on a treadmill. Building off this work, Stone and Hull [7] developed a more advanced strain gauge dynamometer for both the seat and the handlebars that was capable of measuring five load components. Omitted from these measurements were

handlebar M-L forces and seat S-I moments. The resulting figures agreed with the trends found in their earlier study [6]. This experiment was also conducted using the bicycle on treadmill method.

Additional work on seat interface forces was conducted by Wilson and Bush [8], who used a load cell beneath the seat of a standard bicycle on a training stand to evaluate average forces in three directions. Results for 10 participants were reported with average participant S-I, A-P, and M-L forces of 49-52% BW, 11-12% BW, and 4-5% BW, respectively. Further use of force transducers was conducted by Carahalios [9], who instrumented both the seat and handlebar stems of a stationary ergometer with six axis load cells. Peak values of S-I and A-T forces were reported in agreement with peak values for S-I and A-T forces from previous studies [6][7]. Additionally, a relation between power and resultant forces was reported with a 1.0 W/kg increase in power resulting in a 5.2% BW decrease in seat force magnitude and a 1.9% BW increase in handlebar stem force magnitude. Additional research by Vanwalleghem and Mortier et al [10], Drouet and Champoux [11], and Vanwalleghem and Baere et al. [12] was done using bicycles instrumented with strain gauges. However, these studies did not report values for steady state seated cycling. Table 1.1 below shows a summary of the results from the studies cited above. Values were taken from both reported numbers and plots and were normalized by subject body weight. Forces are shown in N/(body weight in N), which is dimensionless, and moments are shown in Nm/(body weight in N) which has units of meters.

Table 1.1: Summary table of results from published literature. All forces are normalized by body weight and all moments by body weight and height.

	Soden & Adeyefa [5] max (abs)	Bolourchi & Hull [6] low high	Stone & Hull [7] low high	Wilson & Bush [8] max (abs)	Carahalios [9] max (abs)
Seat Forces					
M-L [N/N]	N/A	N/A N/A	-0.06 0.08	0.045	N/A
A-P [N/N]	N/A	N/A N/A	-0.19 -0.12	-0.11	-0.20
S-I [N/N]	-0.49	-0.26 -0.20	-0.45 -0.30	-0.52	-0.41
Seat Moments					
M-L [Nm/N]	N/A	0.024 0.059	-0.0022 0.0013	N/A	N/A
A-P [Nm/N]	N/A	-0.010 0.008	-0.0039 0.0029	N/A	N/A
S-I [Nm/N]	N/A	N/A N/A	N/A N/A	N/A	N/A
Handle Forces			(Right Side Only)		
M-L [N/N]	N/A	N/A N/A	N/A N/A	N/A	N/A
A-P [N/N]	N/A	-0.118 -0.069	-0.051 0.096	N/A	-0.12
S-I [N/N]	0.045	-0.173 -0.104	-0.090 0.058	N/A	-0.15
Handle Moments			(Right Side Only)		
M-L [Nm/N]	N/A	N/A N/A	-0.0090 0.0006	N/A	N/A
A-P [Nm/N]	N/A	N/A N/A	-0.0022 0.0026	N/A	N/A
S-I [Nm/N]	N/A	N/A N/A	-0.0003 0.0045	N/A	N/A

Although this work primarily focuses on bicycle seat and handlebar forces, knee joint forces during seated cycling were also considered to help further verify the validity of the OpenSim simulation. Published values for knee joint contact forces during cycling come from both in-vivo measurements and inverse dynamics modeling. In-vivo measurement of compressive and shear contact forces were found by D'Lima et al [13] through the instrumentation of three participants' tibial prostheses. Peak S-I compression and A-P shear forces were found to be 1.03 ± 0.20 times BW and 0.21 ± 0.01 times BW, respectively. Further work was done by Kutzner et al [14], who also used instrumented knee implants to find peak contact S-I compression and A-P shear forces of 1.19 times BW and 0.05-0.07 times BW, respectively. Simulation via a musculoskeletal model was conducted by Neptune and Kautz [15]. This study found a peak tibiofemoral compressive contact load of 1.8 times BW and an A-P shear force of 2.1 times BW. Finally, additional simulation results were reported by Ericson and Nisell [16] with an S-I compressive force of 1.2 times BW and an A-P shear of 0.055 times BW.

1.3 OpenSim Pelvic Residuals: Definition and Published Research

OpenSim is an open source musculoskeletal modeling program developed by Stanford University for biomechanics research [17]. Musculoskeletal modeling programs allow researchers to find values internal to the body, such as knee joint contact loads, which would be very difficult to determine otherwise. This makes OpenSim an invaluable tool to much of the HMBL's research. However, when using OpenSim to analyze activities with complex loading beyond ground reaction forces, the data collection and analysis requirements are increasingly more demanding. For the case of cycling, additional forces must be captured at the seat and handlebars, which requires the use of added equipment and bike modification. Furthermore, when adding these forces to the OpenSim environment, a more complex full body model must be used that can be more difficult to work with. For these reasons, it is desirable to be able to conduct OpenSim analysis on a simple lower body model using only pedal reaction forces. This can be achieved by taking advantage of modeling tools designed to account for dynamic inconsistencies between a model's kinematics and external load data. OpenSim's Residual Reduction Algorithm (RRA) is one such tool.

In computer modeling, real world data often do not align exactly with theory. When conducting biomechanics analysis with numerical tools, there is typically a discrepancy between the recorded motions

of a model's body segments and the external forces acting on the model. Theoretically, for each body segment, these two properties are directly related through Newton's Second Law, Eq. (1), where $\mathbf{F}$ is the total applied external force, m is the mass of the segment, and $\mathbf{a}$ is the acceleration of the center of mass of the segment. However, experimental variability and modeling imperfections preclude the agreement of the applied forces and the body's kinematics. To account for this discrepancy, additional forces and moments, called residuals, are applied to the model by the RRA tool in order to satisfy the second law, as shown in Eq. (2).

$$\mathbf{F} = m\mathbf{a} \quad (1)$$

$$\mathbf{F}_{\text{External}} + \mathbf{F}_{\text{Residual}} = \sum_{i=1}^{\text{segments}} m_i \mathbf{a}_i \quad (2)$$

In Eq. (2), $\mathbf{F}_{\text{External}}$ is the vector sum of all external forces applied to the body minus the body weight vector, m_i is the mass of each body segment of the participant, $\mathbf{a}_i$ is the acceleration of the center of mass of each body segment, and $\mathbf{F}_{\text{Residual}}$ is the residual force vector applied at the pelvis [17]. A similar process is also used to balance the moments applied to the body.

RRA then attempts to reduce these residual forces and moments by altering the center of mass of the model's torso and adjusting the model's joint rotations and body segment trajectories. When applied to a gait trial in which no external forces or moments are acting on the pelvis, RRA should result in residual loads which are close to zero. However, when applied to a cycling trial modeled without seat and handlebar loads, RRA should drive the pelvic residuals to converge on values equivalent to the missing forces and moments. In addition to designing proper seat and handlebar instrumentation, the second research goal of this study is to verify the accuracy of the residual loads applied to the pelvis during OpenSim cycling analysis.

One way to validate the capabilities of RRA is to compare the residual force applied by OpenSim to experimentally measured values. This is similar to the work of Knarr and Higginson [18], who compared the vertical pelvic residual force during gait to the vertical external forces applied to participants when holding treadmill handrails. This research concluded that RRA was fully capable of accounting for this additional loading. Though the work of Knarr and Higginson suggests that RRA is capable of accounting for some external force, validation of the tool when applied to cycling is necessary because the omitted

loads are much greater than those encountered by holding a handrail. An initial look into the accuracy of the pelvic residuals was done by Kraemer and Gutierrez-Franco [4], but the study only considered the raw inverse dynamics results without RRA. Additionally, it was only able to compare the residuals to published data, as Kraemer and Gutierrez-Franco did not have the equipment to collect experimental seat and handlebar data. Their findings indicated that the residuals were within reason when compared to the literature; but with these limitations, a more sophisticated examination is warranted.

Chapter 2

DESIGN AND DEVELOPMENT OF BICYCLE INSTRUMENTATION

2.1 Design

The first step toward reaching the research goals of this thesis was to design an effective way to mount load cells beneath the handlebars and seat of the HMBL's stationary bicycle. The exercise bicycle used by the lab is a LifeCycle GX by Life Fitness, Schiller Park, IL (Figure 2.1).

Figure 2.1: Image of unmodified LifeCycle GX. Image taken from Life Fitness manual [19].

Each of the two mounting locations had its own unique design requirements, but in general any modification of the bicycle should be reversible and should not impinge on natural rider biomechanics or safety. Although the instrumentation conducted in this study should prove useful to further research, the load cells used are shared with other lab equipment and thus cannot be permanently affixed to the bicycle. For this reason, the force transducers must be easily removable without requiring excessive skill or effort on the part of the researcher. Additionally, the modifications must not significantly affect the biomechanics of the participants. If the results of this and future studies are to be broadly applicable to seated cycling in general, the configuration of the experimental equipment must not induce non-typical artifacts into the rider's motion. To ensure that this is the case, the seat and handlebars must retain an appropriate range of adjustability so that proper ergonomics can be achieved for a variety of participant body types. Finally, participant safety is always a top priority, so any design must be structurally sound and devoid of sharp edges or other hazards.

An additional practical consideration is manufacturability. The Cal Poly machine shop is capable of producing a wide variety of parts, but a premium was put on designs that required simpler machining and minimal processing.

2.1.1 Seat Fixture Design

The seat design was the more critical of the two. The seat holds a far greater portion of the rider's weight than the handlebars and is therefore responsible for the largest loads unaccounted for by OpenSim. The seat design also has the additional complexity of setting a lower bound for participant height. Inserting a force transducer in line with the seat post will limit how low the seat can be adjusted, which will in turn limit the minimum participant size. Therefore, designs that are most compact will have the least effect on the range of testable participants and are more favorable.

With these and the above considerations in mind, several initial designs were considered. Early sketches of these designs can be found in Appendix A. The two most promising designs were both modeled in the computer aided design (CAD) program SolidWorks (Dassault Systèmes, Vélizy-Villacoublay, France). The solid models were used to both validate the designs and compare the additional height added to the seat post. A drawing of the comparison is shown in Figure 2.2.

Figure 2.2: Comparison of minimum seat height for two different designs (units in inches).

Although Design 1 shown in Figure 2.2 had the least impact on the minimum seat height, it sacrificed the A-P seat adjustment slider. Design 2 retained all of the adjustability of the original bicycle design while still being compact enough to accommodate riders taller than 160 cm. For this reason, Design 2 was chosen and will be referred to solely hence forth.

The chosen seat design (shown in Figure 2.3) proved to be the best balance of all of the design criteria. It consisted of cutting the seat post in two just below the A-P slider. In order to keep from permanently altering the original bicycle, an additional seat post assembly was purchased from the manufacturer. Two 0.25 inch aluminum plates (named P2 in Figure 2.3) with tapped holes were welded to either side of the now two-piece seat post assembly. This provided sturdy flat surfaces on which to mount the load cell. Two additional aluminum plates (named P1 in Figure 2.3) of the same thickness were machined with holes to match those of the welded plates and the bolt pattern on the load cell. This allowed for easily interchangeable configurations by simply unbolting the load cell if needed or swapping seat post assemblies with the unmodified one. An exploded view of the assembly is shown in Figure 2.3.

Figure 2.3: Exploded view of seat instrumentation assembly.

All aluminum parts were machined using a manual milling machine and the TIG welding was done courtesy of the Cal Poly IME Department. In order to allow for clearance of the TIG torch, the seat post splice location was moved from just below the A-P adjustment slider to roughly 2 cm below it. This modification did impact the minimum seat height but still proved capable of accommodating a 160 cm rider. Counter sunk UNF 10-32 screws were used to attach the two P1 plates to the load cell. Counter sunk UNC 1/4-20 screws were used to fix the P1 and P2 plates together due to the relative strength and ubiquity of this type of screw. Further detail drawings for all of the parts shown can be found in Appendix B. Figure 2.4 shows the completed and assembled seat design.

Figure 2.4: Side view of seat instrumentation assembly.

2.1.2 Handlebar Fixture Design

The handlebar design (shown in Figure 2.5) had less of an impact on cyclist ergonomics. However, because the electronics wiring and power level cable are routed through the handlebar support post, cutting the post was not an option as with the seat design. Instead, mounting brackets had to be designed to interface between the handlebar adjustment slider and the handlebars themselves. This was further complicated by the elliptical cross section of the handlebar adjustment slider. Careful measurements of the existing components were made in order to construct an accurate CAD model in SolidWorks. This

facilitated the design of two brackets, one with a concave elliptical cutout (named B1 in Figure 2.5) and the other with a convex elliptical extrusion (named B2 in Figure 2.5). An additional 0.25 inch plate similar to P1 in Figure 2.3 was required to enable assembly (named P3 in Figure 2.5). This plate differed from P1 only in the size of the outer through holes, which were downsized from UNC 1/4-20 to UNF 10-32 due to space restrictions. Additionally, the eight holes for attaching the plate to the load cell were reduced to four to decrease setup time. The much lower loading seen by the handlebar assembly allowed for the decrease in screw strength associated with these changes. An exploded view of the assembly is shown in Figure 2.5:

Figure 2.5: Exploded view of handlebar instrumentation assembly.

The design and manufacture of brackets B1 and B2 proved to be the most challenging of the project due to the elliptical cross section of the handlebar adjustment slider. Taking accurate measurements of this extruded part was difficult in itself. Calipers were used to measure the most easily accessible dimensions, which were then used to construct a SolidWorks model. Additional measurements were then used to further validate the model's other dimensions. Once the exact elliptical profile had been defined, it was used to create both the convex and concave profiles of B1 and B2. Without access to a horizontal mill

and custom tooling, the only way to fabricate the unusual shapes of B1 and B2 is by computer numeric control (CNC) machining. However, because this can be a time consuming process, the fits of the two brackets were first validated using 3D printed parts (Figure 2.6).

Figure 2.6: 3D printed models of blocks B1 and B2 used to validate geometry.

Both models fit their respective mating surfaces as expected. With the 3D geometry confirmed, two 1 x 2.5 x 3 inch aluminum blocks were prepped for machining. Squaring of the stock and drilling of the holes was done on a manual milling machine and drill press to simplify the CNC process. Once ready, the parts were given to the Cal Poly Mechanical Engineering Machine Shop to cut the complex geometry. A slight alignment error during the CNC setup process resulted in oversized elliptical geometry on the concave section of B1. Luckily, the error was small enough that a few strips of rubberized tape shimmed the gap and made a perfect fit.

Once the machining was completed, all of the parts were assembled as shown in Figure 2.5. B2 was first bolted to the handlebars using two M10x1.5 screws. P3 and B1 were then bolted to either side of the load cell using four UNF 10-32 screws. Next, the assembly of B1, the load cell, and P3 was bolted to the assembly of B2 and the handlebars using four UNF 10-32 screws. Finally, the whole assembly was bolted to the handlebar adjustment slider and attached to the handlebar post via dovetails in the original components. Interchangeability with the original bicycle configuration was not as easy as with the seat design. However, the entire operation described above could still be completed by a knowledgeable operator in less than 15 minutes. Further detail drawings for all of the parts shown can be found in Appendix B. Figure 2.7 shows the completed and assembled handlebar design.

Figure 2.7: Side view of handlebar instrumentation assembly.

Note that the instrumentation design raises the handlebars by 10.6 cm from their original position. However, this is not an ergonomic concern because there is plenty of adjustability built into the handlebar post to counteract the increase in handlebar height and the new handlebar position does not interfere with the rider's view of the bicycle instrument panel.

2.2 Calibration Check

The two force transducers chosen for this study are six axis AD2.5D-1000 load cells (AMTI Watertown, MA), which come pre-calibrated from the manufacturer to account for manufacturing differences and cross talk. The manufacturer is in possession of high quality calibration equipment that far exceeds the capabilities of this lab. However, potential disturbances over the life of the transducers, errors in the manufacturing of the mounting brackets, and errors in the transducer origin finding method are all causes for concern. For these reasons, it is important to verify the output of the transducers as used in this application.

In order to effectively verify the calibration of the system, it is necessary to apply known forces and moments to each of the load cells. This poses two challenges; knowing the magnitude of the applied force and the direction of its application. Exercise weights proved to be the best source of load due to their availability and repeatability. Once the mass of the weights was confirmed by a lab scale, they could be used to reliably apply a known force. This was easily accomplished in the vertical direction by simply

placing the weights on the top surface of the transducers. To apply a horizontal load, a wooden calibration frame with a low friction pulley was constructed. The HMBL utilizes an optical motion capture system for all of its experimental research (Motion Analysis, Santa Rosa, CA). This allowed for easy determination of the electrical origins of the force transducers as well as the direction of the applied horizontal loads. Retro-reflective markers were placed around the transducer origins and were also threaded onto a length of sturdy cord. The marked cord was then used with the calibration frame and weights to apply a known force in a known direction. To allow for adjustability in the load application point, an additional frame made from extruded aluminum channel was built and bolted onto the force transducer. Figure 2.8 shows the weights, calibration frame, marked rope, and aluminum frame being utilized.

Figure 2.8: Calibration check test applying an inferior and posterior force and a lateral moment to the bicycle seat load cell. Bright dots in the image are retro-reflective markers used to locate key positions in the setup.

The primary goal of this calibration check is to ensure that the force transducers output correct values over the typical range of forces and moments exerted on the seat and handlebars. Typical loading found in preliminary cycling tests and published literature was used to design three test cases for both the seat and handlebars. In each case, two forces and one moment were applied at magnitudes roughly proportional to those seen in cycling. The typical loads and test loads for a 71.5 kg rider are shown in Table

2.1 and Table 2.2. The number of possible test cases that met the proportional requirement was restricted by the size and quantity of weights available in the lab. Positive and negative values are defined by the lab axis with positive up, posterior, and left of the rider. The typical loads were values observed in preliminary tests and in the literature for an averaged sized male rider pedaling at 70 revolutions per minute (RPM) and a moderate bike power level of 10.

Table 2.1: Typical seat loads during seated cycling and calibration check test cases.

	Anterior-Posterior Force [N]	Superior-Inferior Force [N]	Medial-Lateral Moment [Nm]
Typical Loads	80.0	-500.0	-25.0
Trial 1	23.1	-215.8	-7.3
Trial 2	57.4	-409.6	-18.1
Trial 3	91.2	-619.5	-28.9

Table 2.2: Typical handlebar loads during seated cycling and calibration check test cases.

	Anterior-Posterior Force [N]	Superior-Inferior Force [N]	Medial-Lateral Moment [Nm]
Typical Loads	-100.0	-100.0	10.0
Trial 1	-22.1	-22.6	2.5
Trial 2	-44.6	-44.8	5.1
Trial 3	-161.3	-166.6	18.3

Force and position data were captured using Motion Analysis's Cortex software at 150Hz and averaged over a 10 second period. Further post processing was carried out in Microsoft Excel. The load cell centers of pressure were found by averaging the position of the attached markers. The load application point and direction of the force applied from the calibration frame were found by creating a vector from the positions of the two markers threaded onto the rope. Using the applied force vector, the distance between the application point and the electrical origin, and the known weight added directly above the electrical origin, the total loading of the force transducer was calculated. This loading could then be compared to the outputs of the force transducers.

To analyze the results, plots of expected values versus measured values were made for all of the force and moment components. A positive test result is defined by two linear regression criteria: a linear transducer response indicated by an R^2 of approximately 1 and an accurate transducer response indicated by a slope of approximately 1 and a y-intercept of approximately zero. Both of these criteria were met for all of the components measured. This confirms that the force transducers could be reliably used in this application. The rest of the study could thus proceed with a large degree of confidence in the measured seat and handlebar load data. An example plot of the calibration results is shown in Figure 2.9 Plots of all calibration results are provided in Appendix C.

Figure 2.9: Seat anterior-posterior force calibration check results.

Chapter 3

METHODS

The seat and handlebar instrumentation allowed for the direct study of the OpenSim pelvic residuals. When analyzing gait using ground reaction forces, all pelvic residual loads should theoretically be zero because no additional external forces are acting on the body. However, this is rarely the case in OpenSim due to modeling and data collection inaccuracies. For this reason, OpenSim provides guidelines for the maximum peak pelvic residual forces and moments for gait. This is possible because the residual error bars for gait are with respect to zero and therefore are always constant. In cycling, where external loads beyond pedal forces are applied, this is not the case. The true pelvic residual fluctuates with the additional external loads. Therefore, to confirm that the RRA pelvic residuals are within acceptable error bars, an equivalent force couple system at the pelvis due to the seat and handlebar loads must be determined. The following procedure aims to accomplish this by: (1) finding the RRA pelvic residuals, using pedal loads and traditional OpenSim procedures, and (2) finding a handlebar seat equivalent (HBSE) at the pelvis through the use of the additional seat and handlebar load cells. By using the HBSE as a moving true residual and comparing that to the output from RRA, the true errors in OpenSim RRA pelvic residuals can be determined and compared to recommended values.

3.1 Participant Selection and Informed Consent

All protocols followed for this study were approved by Cal Poly's Institutional Review Board (IRB). Participant selection for the OpenSim pelvic residual analysis portion of this study was straightforward. The purpose of this part of the study is to examine the OpenSim RRA tool's ability to correctly characterize external loads that are not accounted for directly and to apply appropriate resultants to the pelvis. To be considered acceptable, this process should work for all ranges of participant sizes and body types. This is, simply put, an experiment designed to test the experimental equipment rather than an experiment designed to test a specific group of individuals. Five participants were analyzed for this study. Table 3.1 shows some general information for each of the five participants.

Table 3.1: General information for five research participants.

Participant ID	Age [yrs]	Height [cm]	Weight [kg]
2018July06-01	23	162.7	57.4
2018July07-01	24	162.9	56.5
2018July13-01	23	177.7	71.5
2018Sep04-01	22	158.9	49.6
2018Nov09-01	52	176.4	83.3
Average	28.8	167.7	63.63

Before conducting the experiments, each participant was given a copy of the IRB protocol, informed consent form, Physical Activity Readiness Questionnaire (PAR-Q), Photographic Image Release Agreements, and Test Participant Information form. After given ample time to read over all of the forms, ask questions, and sign each document, each participant's height and weight was recorded. This completed the pre-experimental procedure.

3.2 Experimental Equipment

Kinematic data for all trials were captured using a motion capture system by Motion Analysis Corp. This system consisted of twelve Motion Analysis digital cameras; two Eagle cameras (Figure 3.1), one Kestrel camera, three Osprey cameras, and six Owl cameras. The two Eagles and six Owls were mounted evenly around the room's parameter walls, while the three Osprey and Kestrel cameras were mounted on movable tripods. A set of 20mm retro-reflective markers, also by Motion Analysis, were used as tracking objects for the cameras. Adhesive hook and loop stickers were used to attach the markers to places of interest.

Kinetic data were captured using two AMTI AD2.5D-250 load cells rated to 250 lb and two AMTI AD2.5D-1000 load cells rated to 1000 lb (Figure 3.1). The two 250 lb load cells were used to capture reaction forces at the pedals, while the two 1000 lb load cells were used to capture seat and handlebar reactions (as described previously). All load cells were driven by AMTI Gen 5 signal conditioners and zeroed through AMTI's NetForce software. All measured kinematic and kinetic data were captured though

Cortex version 7.01 software by Motion Analysis. Capture times ranged from 1 min 30 sec to 2 min depending on the trial. Both marker data and load data were recorded at 150 Hz.

The final piece of equipment used was an instrumented stationary exercise bicycle (Figure 3.1). The model used was a Lifecycle GX. This model has an instrument panel where participants can see their cycling cadence in RPM and an indicator showing the current resistance setting of the bicycle. The resistance setting ranges from 0-20 and is set by adjusting a plastic lever mounted to the handlebar post. The bicycle pedals were instrumented with the load cells described above by prior HMBL students [4], while the seat and handlebars were custom designed for this study.

Figure 3.1: Motion analysis eagle camera (left), AMTI AD2.5D-1000 load cell (middle), and instrumented Lifecycle GX (right).

3.3 Experimental Protocol

All equipment was turned on the day of the experiment and was given an hour to warm up before calibration of both the cameras and the load cells. At the beginning of each experiment, the participants were given ample time to complete all necessary consent and release paperwork. Once finished, if the participant had no further questions and was deemed able to participate in the study based on the experimental requirements, they were instructed to change into compression clothing and their height and weight were recorded. The participant was then outfitted with 31 hook and loop stickers placed at anatomical locations defined by the advanced Helen Hayes marker set (Figure 3.2).

Figure 3.2: Advanced Helen Hayes markerset. Image reproduced from Dudum [20].

The 32nd marker defined the top of the head and was placed on a hat rather than on the participant. Retro-reflective markers were then placed on all of the hook and loop stickers except for those on the medial knees and ankles. The medial markers would be used later in the study during the static pose but had a tendency to hit the bike frame when cycling so were omitted for dynamic trials. After all of the necessary markers had been placed, cycling trials began. The trial began with the participant off of the bicycle and out of the capture volume. This allowed for clean initial force and position data for the load cells to be collected for use in post processing. After waiting approximately five seconds, the participant was instructed to mount the bicycle and pedal up to 70 RPM at a moderate resistance of 10 out of 20. Once at the target cadence, 30 more seconds of data were collected before ending the capture. Three such trials were taken for each subject. After all of the trials were concluded, the medial markers and top head marker hat were placed on the participant in order to take a static trial. Static trials were captured in order to facilitate OpenSim scaling and consisted of the participant standing at the center of the capture volume with his or her feet shoulder width apart and arms held out from the body. Once the participant was in position, they were instructed to stay as still as possible while three quick captures of only a few frames were taken. This completed the data capture portion of the study. The retro-reflective markers were removed and the participant was allowed to change back into street cloths. All equipment was then shut down, concluding the experiment.

3.4 Analysis

Once all of the raw data for an experiment had been collected, a series of post processing steps were required. These steps took place in several different software environments and are outlined in the following sections. When describing or presenting cycling data, one cycle is defined by one revolution of the right pedal, starting at top center and moving in a clockwise direction.

3.4.1 Cortex Processing

The post processing procedure began in Cortex by defining the markers in the static pose. Each marker in the Helen Hayes marker set was identified for all frames in the capture (Figure 3.3). This allowed Cortex to create a .trc file containing all of the marker positions (kinematic data) for that trial. Once the static trial was complete, the individual cycling trials were processed. Each trial was split into two separate regions of interest. The first region contained the few seconds at the start of each trial where the participant was standing outside of the capture volume. From this region, the initial hardware conditions such as load cell locations and zero force readings were captured. The second region consisted of 10 seconds of steady state cycling at 70 RPM. All files pertaining to the first region had the identifier “Forces” added to the end of the filenames. This included a Forces.trc file that contained the positions of the load cells and a Forces.anp file that contained their initial load measurements. The region containing steady state cycling was processed in a similar way to the static trial. Files used in this region had the identifier “processed” added to the end of the filename. Once all of the markers had been identified, a processed.trc and a processed.kin file containing kinematic and kinetic data for the trial, respectively, were generated. All of the kinematic marker data were filtered in Cortex using a 4th order Butterworth filter with a cutoff frequency of 6 Hz.

Figure 3.3: Participant in static pose (left) and processed static pose in Cortex (right).

Before the files could be used in the OpenSim environment, an additional intermediate step was required. OpenSim uses a different coordinate and unit system than the HMBL so all Cortex output files were run through a proprietary conversion code written in MatLab (MathWorks, Natick, MA). This script also applied a 4th order Butterworth filter with a cutoff frequency of 6 HZ to all load cell data. More information on this code can be found in Orekhov, 2018 [21]. Further post processing of each trial was completed in two separate workflows, one producing the OpenSim pelvic residual, and the other finding the HBSE.

The OpenSim workflow followed standard procedures as discussed in further detail in the next section. It utilized the pedal loads contained in the processed.anp file and the static and dynamic marker data contained in .trc files. The result of this process was pelvic residuals produced by the RRA tool. These residuals are an estimate of the seat and handlebar loads resolved at the pelvic origin.

The second workflow is unique to this study and served to check the results from RRA. To accomplish this, seat and handlebar load cell data from the processed.anp and Forces.anp files were used along with marker data from the processed.trc and Forces.trc files to create an equivalent combined force system at the pelvis called the HBSE. If RRA is correctly accounting for the seat and handlebar loads, the pelvic residuals should be equal to the HBSE loads within the recommended error bars.

3.4.2 OpenSim Processing for Pelvic Residual

OpenSim is an open source musculoskeletal modeling environment developed by Stanford University to allow researchers to determine forces and moments internal to the body. This tool is invaluable compared to traditional inverse dynamics calculations because it takes into account the loads at the body's joints due to muscle activation. Without accounting for such loads, proper determination of joint contact forces would be impossible. This research attempts to support the use of OpenSim for cycling applications by providing insight into the program's ability to account for external seat and handlebar loads that are omitted as a simulation input. This requires each participant to be processed through the OpenSim RRA tool where the pelvic residual loads are calculated. However, processing of each participant was taken further through the OpenSim workflow in order to help verify the model selection and provide additional information for future studies. Figure 3.4 on the following page shows an example of a cycling participant in OpenSim alongside a picture of a participant mid trial and in Cortex. The same Helen Hayes marker set is used to define the position of the skeleton in OpenSim as in Cortex. The markers are displayed as white dots in the picture, blue crosses in Cortex, and pink dots in OpenSim. The red lines in the OpenSim image show approximations of human muscles. OpenSim will use activation of these muscles to drive the model's motion in later processing.

Figure 3.4: Cycling participant shown mid trial, processed in Cortex, and processed in OpenSim.

Model selection is one of the most important modeling choices in the OpenSim environment. Many models have been developed over the years with varying degrees of accuracy and intended use. One of the most common OpenSim models is the Gait 2392 model developed by Delp et al. [22]. This 23-degree of freedom model was developed primarily for gait analysis and therefore has known issues when applied to activities with high knee flexion such as cycling. Typical HMBL cycling results from simulations run with Gait 2392 show greater than anticipated A-P shear loads at the knee [2]. To address the issues with Gait 2392, a model was developed by Lai and Arnold [23] that is capable of producing more accurate results at high hip and knee flexion angles. The “LaiArnold” model is capable of simulating 120 degrees of hip flexion and 140 degrees of knee flexion due to adjustments made to the model’s muscle paths and force properties. As part of the OpenSim analysis for this study, a comparison between the two models was made in order to determine which would be better suited for future HMBL cycling research. Knee joint contact forces from the LaiArnold model and the Gait 2392 model are compared in Appendix D. As anticipated, the LaiArnold model produces far more reasonable results for cycling knee biomechanics. Further OpenSim analysis and discussion will pertain to results obtained using the LaiArnold model. The OpenSim workflow contains five crucial steps which are shown in Figure 3.5 and will be outlined in more detail below.

Figure 3.5: Flowchart of the five analysis tools used in OpenSim processing. The inputs to each tool are shown on the left with outputs shown on the right. Image reproduced from Pottinger [2].

Scale Tool: The scale tool allows for the creation of a subject specific model. Each OpenSim model has a generic height and weight assigned to it as well as generic body segment lengths and mass distributions. In order to get accurate simulation results, the generic model must be “scaled” to better match the real participant. This is achieved by first moving virtual markers on the generic model to locations better representing the positions of the actual markers placed on the participant. When the scale tool is run, OpenSim will manipulate the generic model to match the virtual markers as closely as possible to the experimental markers provided from the static trial. This is typically an iterative process that requires the virtual markers in the generic model to be manually moved many times. Iteration continues until the largest absolute error between each virtual and experimental marker pair is under 0.02 m. If this criteria is met and the resulting model does not exhibit any non-physiological joint rotations, the model is considered scaled.

Inverse Kinematics (IK): The IK tool is the first tool applied to a subject specific scaled model. The purpose of the IK tool is to translate the dynamic cycling trial data into the OpenSim environment. This is accomplished by analyzing each frame of the .trc file and placing the scaled model in an orientation that best aligns the virtual and experimental markers. A weighted squared errors method is used to find the optimum balance between all of the markers. This process is similar to the Scale Tool except in IK, the model's dimensions are fixed. Once the entire trial is processed, the IK tool outputs a results file that contains the model's optimal joint trajectories.

Residual Reduction Algorithm (RRA): The RRA tool is responsible for attempting to merge the kinematics from IK with the load data from the ground reaction forces (GRFs) measured experimentally. Discrepancies between the kinematics and the load cell data, due to both modeling and experimental errors, lead to the formation of large residual forces that OpenSim applies to the pelvic origin (Eq. (2)).

$$\mathbf{F}_{\text{External}} + \mathbf{F}_{\text{Residual}} = \sum_{i=1}^{\text{segments}} m_i \mathbf{a}_i \quad (2)$$

These forces can at times be necessary, such as when they stand in for forces not accounted for experimentally, but are considered by OpenSim to be errors. This is because OpenSim is primarily designed for analyzing gait in which no external loading beyond the GRFs is applied to the body. RRA therefore seeks to reduce the pelvic residuals by shifting the location of the torso mass center, rearranging the body segment mass distribution, and altering the IK results to better match what would be induced by the GRFs. The torso mass center is typically chosen as the body segment to adjust because it is the most massive and least easily estimated of the model. RRA has many outputs, but the one of most concern to this study is the reduced pelvic residuals file. The pelvic residuals are the main target of this research and will be compared to the HBSE in order to draw conclusions as to the ability of OpenSim to adequately account for seat and handlebar loads. RRA is the last OpenSim tool required for this study. However, two additional tools were used to provide extra information that may be useful to future studies.

Static Optimization (SO): The SO tool breaks the motion of the body down into the result of individual muscle activations. The LaiArnold model contains 84 actuators that are responsible for simulating the behavior of the actual muscles in the human body. SO uses inverse dynamics to calculate the net joint moments for each frame in time. These moments are then broken down into resultant torques

caused by the actuators. An algorithm that minimizes the sum of the squared muscle activations is used to determine the individual muscle forces. It is this step in which model selection has the most effect. The precise location of the actuators in the model along with their force properties has a large effect on the results from SO. After SO has analyzed the entire trial, it outputs a file containing all of the activation forces of each muscle activator over time.

Joint Reactions (JR): The results from JR are the typical goal for most OpenSim experiments. JR uses the adjusted model and kinematics from RRA and the muscle activation forces from SO in order to calculate the total resultant joint contact loads of the model. This analysis takes both the external and internal forces into account to give a far more accurate estimation of internal joint contact loading than inverse dynamics alone. Although the objective of this study is not to report joint contact loads, loading of the right knee for each of the participants analyzed is provided for reference in Appendix E.

3.4.3 MatLab Processing for HBSE

The post processing required to obtain the HBSE was accomplished in MatLab. A custom program was written to import all of the relevant information, zero the initial load cell readouts, find the locations of the load cell electrical origins, perform the arithmetic required to transform the seat and handlebar loads to the pelvic origin, and finally plot all of the results. In order to accomplish this, the program had to import many files. First were the Forces.trc and Forces.anp files, which contained the positions and initial tare values of the seat and handlebar load cells, respectively. Further information was loaded in the processed.trc and processed.anp files, which contained the locations of the pelvic origin though time and the seat and handlebar loads though time, respectively. Finally, the .sto file from OpenSim RRA containing the pelvic residuals was loaded for generating comparison plots later. After the data were imported, the program used the Forces.anp file to tare the seat and handlebar data from the processed.anp file. This step was largely unnecessary because the load cells were always hardware zeroed before each study, but small non-zero readings were occasionally noted at the beginning of some trials. These were likely due to the increased forces and torques applied to the seat and handlebars as the rider dismounted the bike between trials. To ensure consistency across participant data, all of the load data were subtracted by the tare values in software. Once the kinetic data were prepped, the Forces.trc and processed.trc files were

used to find vectors from the pelvic origin to the electrical origins of the seat and handlebar load cells. The load cells were assumed to be stationary throughout the trial, which allowed their position to be determined from a brief period at the beginning of each trial when the participant was outside of the capture area. This was a necessary assumption because, due to the locations of the load cells, the markers which were used to define their origins were often obscured by the rider. The pelvic origin, however, is expected to move as the rider pedals through a full cycle, so its position was taken into account frame by frame when calculating the distance vectors. With accurate load and distance information, the seat and handlebar forces and moments could be translated to the pelvic origin, generating the HBSE. The calculations required to do so are outlined in equations (3) and (4) below.

$$\mathbf{F}_{HBSE} = \mathbf{F}_{Seat} + \mathbf{F}_{Handle} \quad (3)$$

$$\mathbf{M}_{HBSE} = (\mathbf{M}_{Seat} + \mathbf{M}_{Handle}) + [(\mathbf{r}_{Pelvis \rightarrow Seat} \times \mathbf{F}_{Seat}) + (\mathbf{r}_{Pelvis \rightarrow Handle} \times \mathbf{F}_{Handle})] \quad (4)$$

Where $\mathbf{F}_{HBSE}$ is the net resultant combined force, $\mathbf{F}_{Seat}$ and $\mathbf{F}_{Handle}$ are the seat and handlebar forces to be resolved at the hip center, $\mathbf{M}_{HBSE}$ is the net resultant combined moment, $\mathbf{M}_{Seat}$ and $\mathbf{M}_{Handle}$ are the seat and handlebar moments to be combined, and $\mathbf{r}_{Pelvis \rightarrow Seat}$ and $\mathbf{r}_{Pelvis \rightarrow Handle}$ are the vectors from the pelvic origin to the locations of the seat and handlebar load cell centers, respectively. Figure 3.6 shows a diagram of the vectors involved in the above calculations.

Figure 3.6: Diagram showing locations of vectors involved in HBSE calculation. Force and moment vectors are shown in arbitrary directions.

Once the new equivalent force couple system was created at the location of the pelvic origin, it could be directly compared both graphically and statistically to the OpenSim results contained in the .sto file from RRA. See Appendix F for MatLab code used in this analysis.

3.4.4 Statistical Analysis

In order to statistically analyze the difference between results generated by RRA and calculated through the handlebar seat equivalent (HBSE), a set of four sequential crank cycles per trial were randomly selected. The decision to include multiple correlated crank cycles per trial resulted in the need for a more complex statistical model. However, this was worth the added complexity because it allowed for more data to be retained in the model. The data were then simplified by considering only the peak RRA and HBSE values for each load direction per crank cycle. This was done to simplify the statistical model but is an acceptable simplification because peak values are typically the most important when studying internal forces in biomechanics. Given that each trial contained four cycles, each participant underwent three trials, and there were a total of five participants, a grand total of 60 variable pairs, or 120 total observations, were analyzed per load direction. Table 3.2 shows an example data set prepared for statistical analysis.

Table 3.2: Sample of data formatted for statistical analysis.

Person	Trial	Cycle	Label	Peak AP F [N/N]	Peak SI F [N/N]	Peak ML F [N/N]	Peak AP M [Nm/Nm]	Peak SI M [Nm/Nm]	Peak ML M [Nm/Nm]
1	1	1	HBSE	-0.0656	0.9996	0.0836	-0.0292	-0.0122	0.0495
1	1	1	RRA	-0.1000	0.9655	0.0349	-0.0067	-0.0117	0.0323
1	1	2	HBSE	-0.0562	1.0058	0.0695	-0.0291	-0.0112	0.0537
1	1	2	RRA	-0.0734	1.0015	0.0418	-0.0073	-0.0113	0.0314

The data from all of the six force and moment directions were analyzed using a mixed model with repeated measures in SAS (SAS Institute Incorporated, Cary, NC). Because the peak values of each of the four cycles were potentially correlated with the adjacent peaks, analysis of the cycles was nested within each trial. The cycles were analyzed using a first order autoregressive correlation structure. This functioned by assuming that two adjacent peaks have a correlation of r where r is a number less than 1. For example, the peak A-P force in cycle 1 is assumed to be correlated with the peak A-P force in cycle 2 by a factor of r . The correlation factor then decreased exponentially as further peaks were considered. Continuing the same example, if the peak A-P forces from cycles 1 and 2 have correlation r , then the peak A-P forces from

cycles 1 and 3 have correlation r^2 and the peak A-P forces from cycles 1 and 4 have correlation r^3 . All parameters were estimated by a restricted form of maximum likelihood estimation (REML). REML was chosen because it allowed for the changing variance structure associated with the first order autoregressive correlation structure. This is in contrast to ANOVA analysis, which requires a fixed variance structure. The model tested for significance in the difference between data points from the RRA set and data points from the HBSE set and generated a 95% confidence interval for the difference. See Appendix G for additional details, example code, and raw outputs from SAS.

Chapter 4

RESULTS

4.1 Seat and Handlebar Load Results

Load data from the seat and handlebar force transducers were compared to the literature in order to ensure that the instrumented bicycle system was producing reasonable results. The magnitude and distribution of loads a cyclist exerts on a bicycle varies greatly with rider, riding position, style of bicycle, and power exertion. Therefore it is unlikely that any two experimental setups will be directly comparable in terms of individual loads. However, general trends can be analyzed to determine what is typical of seated cycling. Table 4.1 below is a reproduction of Table 1.1 with the addition of data from this study added in gray. See Appendix H for plots of raw load cell data.

Table 4.1: Summary table of results from published literature with the addition of results from this study.

All forces are normalized by body weight and all moments by body weight and height.

	Soden & Adeyefa [5] max (abs)	Bolourchi & Hull [6] low high	Stone & Hull [7] low high	Wilson & Bush [8] max (abs)	Carahalios [9] max (abs)	Wash low high
Seat Forces						
M-L [N/N]	N/A	N/A N/A	-0.06 0.08	0.045	N/A	-0.05 0.05
A-P [N/N]	N/A	N/A N/A	-0.19 -0.12	-0.11	-0.20	-0.20 0.00
S-I [N/N]	-0.49	-0.26 -0.20	-0.45 -0.30	-0.52	-0.41	-0.85 -0.50
Seat Moments						
M-L [Nm/N]	N/A	0.024 0.059	-0.0022 0.0013	N/A	N/A	0.007 0.042
A-P [Nm/N]	N/A	-0.010 0.008	-0.0039 0.0029	N/A	N/A	-0.007 0.006
S-I [Nm/N]	N/A	N/A N/A	N/A N/A	N/A	N/A	-0.002 0.005
Handle Forces			(Right Side Only)			
M-L [N/N]	N/A	N/A N/A	N/A N/A	N/A	N/A	-0.03 0.03
A-P [N/N]	N/A	-0.118 -0.069	-0.051 0.096	N/A	-0.12	0.075 0.23
S-I [N/N]	0.045	-0.173 -0.104	-0.090 0.058	N/A	-0.15	-0.15 -0.06
Handle Moments			(Right Side Only)			
M-L [Nm/N]	N/A	N/A N/A	-0.0090 0.0006	N/A	N/A	-0.013 -0.003
A-P [Nm/N]	N/A	N/A N/A	-0.0022 0.0026	N/A	N/A	-0.009 0.008
S-I [Nm/N]	N/A	N/A N/A	-0.0003 0.0045	N/A	N/A	-0.010 0.008

Typically, results from this study matched the range of expected values with a few notable exceptions. The seat S-I forces and handlebar A-P forces observed in this study were more negative and more positive, respectively, than those found in other studies. Additionally, both the seat S-I moment and the handlebar M-L force were not reported by any other study and thus cannot be compared. Appendix I contains additional graphical comparisons of data collected in this study to results from published literature.

4.2 OpenSim RRA Results

Analysis of the results from RRA was accomplished through direct comparison to the HBSE. Although the HBSE was also derived from experimental measurements, the seat and handlebar data used were reasonable when compared to published literature. It can therefore be assumed that the experimental error within these measurements is small and that the transformation of the loads to the pelvis introduces minimal additional error. Therefore, for the purpose of this analysis, the HBSE results are assumed to be as near to exact as is reasonably obtainable. Figures 4.1 through 4.3 show sample plots comparing RRA and HBSE results for a typical participant. See Appendix J for a complete comparison across all subjects and load directions.

Figure 4.1: Three cycle RRA and HBSE anterior-posterior force comparison from the first trial of participant 2018July06-01. Plots are normalized by body weight.

Figure 4.2: Three cycle RRA and HBSE superior-inferior force comparison from the first trial of participant 2018July06-01. Plots are normalized by body weight.

Figure 4.3: Three cycle RRA and HBSE anterior-posterior moment comparison from the first trial of participant 2018July06-01. Plots are normalized by body weight and height.

The above three plots are reasonably representative of the trends seen across all participants and load directions. Typically, forces show more visual correlation than moments for most participants. OpenSim is known to produce more accurate results for forces than for moments so these results are not unexpected. Additionally, visual comparisons between participants show no correlation between RRA accuracy and body mass. The accuracy of the results from RRA is likely due to other factors such as the quality of the experimental marker data.

In addition to comparing the results visually, RRA and HBSE data were analyzed statistically. Normalized peak values for four cycles of each trial were analyzed in SAS. The model tested the hypothesis that there is no statistical difference between results from RRA and HBSE and additionally calculated a 95% confidence interval for their difference. Table 4.2 shows a summary of the statistical results. Load directions that showed a statistically significant difference between RRA and HBSE results are highlighted in gray. See Appendix G for additional statistics information and raw outputs from SAS.

Table 4.2: Summary table of statistical analysis comparing RRA and HBSE results. Load directions that show significant differences are highlighted in gray.

Load Direction	Pr > t	Mean Difference	95% Confidence
A-P Force	0.0673	0.00964	(-0.00074;0.02002)
M-L Force	<0.0001	0.01139	(0.00692;0.01586)
S-I Force	<0.0001	0.03847	(0.02451;0.05243)
A-P Moment	<0.0001	-0.02609	(-0.02900;-0.02318)
M-L Moment	0.0001	0.01687	(0.009339;0.02441)
S-I Moment	0.7284	-0.00016	(-0.00111;0.00079)

While the A-P force and S-I moment loads show no significant difference between RRA and HBSE results, the remaining load directions all show a statistically significant difference. This can be identified by a low P-value and a confidence interval that does not contain zero. Note that differences in both the mean differences and the confidence intervals are expressed in normalized terms. For example, the mean difference for M-L Force is 1.139% BW and the confidence interval for the M-L moment difference is from 0.9339% to 2.441% BW*height.

Chapter 5

Discussion

5.1 Discussion of Seat and Handlebar Load Results

The first major goal of this research was to instrument a stationary exercise bicycle with force transducers on the seat and handlebars for use in a variety of future studies. This objective was met with a high degree of confidence based on the supporting evidence. Initial testing of the seat and handlebar transducers using weights and the calibration frame yielded measured loads which accurately predicted the expected loads. Ideally, plots correlating the measured and expected loads should each have a slope of 1, a y intercept of 0 N, and an R^2 of 1. Plots for the six force and moment directions all showed slopes between 0.99 and 1.05, Y-intercepts between -0.29 N and 0.56 N, and R^2 values greater than 0.999. Deviations from the ideal values indicated some inconsistencies between the measured and expected values, however, the errors are well within the accuracy of the equipment used in the calibration check setup and give no reason to doubt the accuracy of the instrumented bicycle.

Additionally, comparisons of cycling data captured using the bicycle instrumented in this study to other published literature showed strong agreement across most load directions. The few exceptions can be explained by differences in power level and ergonomics of the bicycle. This study found a lower peak S-I force than all of the other studies. However, this is explainable by the moderate power level used in this study compared to the higher power output of the more advanced cyclists in other research. As power level is increased, more of the cyclist's weight shifts from the seat to the pedals, thus increasing the magnitude of the S-I force acting on the bike. Another discrepancy is in the handle A-P forces where this study found much larger values. This is likely due to a combination of power level and ergonomics. As power level increases, a lower or even negative handlebar A-P force is often seen as the rider pulls back on the handlebars during the left or right pedals power stroke. Additionally, the highest A-P handlebar forces were seen by one of the smallest participants who likely rode with the seat set too far back. This would have caused the participant to lean abnormally forward exerting a higher than typical A-P force on the handlebars. All of the other load directions showed a reasonable range compared to published literature. Seat S-I moment and handlebar M-L force were not reported by any of the studies examined in this report but also seem to have reasonably ranged values when compared to other force or moment directions.

5.2 Discussion of OpenSim RRA Results

The second major goal of this research was to confirm the accuracy of the OpenSim pelvic residual loads calculated during RRA by directly comparing them to the HBSE loads. The graphical comparison of these results yielded two major observations. In general, RRA is more capable of accounting for external forces than for moments, and within the sample size of this study, there is no apparent relationship between body weight and RRA accuracy. Trials with data that shows weaker visual RRA and HBSE correlation also had issues during experimentation such as markers placed by less experienced lab personnel and non-ideal bicycle location within the capture volume. These factors likely have a much greater effect on RRA accuracy than any other participant-to-participant variable. Small improvements to both marker placement accuracy and marker data capture quality yield large improvement to simulation accuracy.

Statistical analysis of the data showed significant differences between peak RRA and HBSE values for M-L and S-I forces as well as A-P and M-L moments. These results show that RRA is typically overestimating M-L and S-I forces as well as M-L moments and typically underestimating A-P moments. The OpenSim guidelines for maximum pelvic residual loads when modeling gait are less than 25 N for forces (ideally less than 10 N) and less than 75 Nm for moments (ideally less than 50 Nm) [24] as shown in Table 5.1. In gait, no external forces act on the pelvis, so all residual loads should theoretically be zero. However, in cycling, these error bars can be considered acceptable deviations from the true residual captured by the HBSE. However, in order to compare the error recommendations from OpenSim to the results from this study, they were normalized by the average participant height and weight of 167.7 cm and 63.6 kg, respectively. Table 5.1 shows the maximum residual forces and moments recommended by OpenSim both in absolute and normalized units.

Table 5.1: Recommendations for maximum residual forces and moments. Absolute values are taken directly from OpenSim’s recommendations [24] while normalized values are specific to the average participant height and weight of this study. Green is good (normal text), yellow is okay (italicized), and red is bad (bolded).

Absolute Recommendations			
Threshold	GOOD	OKAY	BAD
Max Residual Force (N)	10	25	>25
Max Residual Moment (Nm)	50	75	>75

Normalized Recommendations			
Threshold	GOOD	OKAY	BAD
Max Residual Force (N/N)	0.016	<i>0.040</i>	>0.040
Max Residual Moment (Nm/Nm)	0.048	<i>0.072</i>	>0.072

Examining these normalized results, OpenSim’s guidelines indicate that a $\pm 4.0\%$ BW error for forces and a $\pm 7.2\%$ BW*height error for moments is “OKAY”. Because the HBSE forces and moments are considered to be the true residual, the statistical difference between the HBSE peaks and the RRA pelvic residual peaks can be directly compared to the normalized error recommendations provided by OpenSim. Table 5.2 shows the statistical results from this study color coded to reflect the normalized recommendations from Table 5.1.

Table 5.2: Statistical results for RRA pelvic residuals verses HBSE color coded based on normalized OpenSim RRA error recommendations. Green is good (normal text), yellow is okay (italicized), and red is bad (bolded).

Load Direction	Mean Difference	95% Confidence	
		Lower	Upper
A-P Force	0.00964	-0.00074	<i>0.02002</i>
M-L Force	0.01139	0.00692	0.01586
S-I Force	<i>0.03847</i>	<i>0.02451</i>	0.05243
A-P Moment	-0.02609	-0.029	-0.02318
M-L Moment	0.01687	0.009339	0.02441
S-I Moment	-0.00016	-0.00111	0.00079

Table 5.2 shows that all of the mean errors found in this study are below the acceptable thresholds set by OpenSim. The superior-inferior force direction shows the largest average error, but majority of the confidence interval is still within the “OKAY” region. Therefore, there is no evidence to suggest that the

true population mean error for S-I force is outside of the acceptable range. Additionally, OpenSim advises that activities with faster body motion, such as cycling, will tend to have higher residual errors. Based on these observations, it is reasonable to conclude that when analyzing seated cycling in OpenSim, the RRA tool produces pelvic residuals that are within the recommended error thresholds.

5.3 Limitations and Future Work

Although the stationary bicycle instrumented in this study is fully capable of accurately capturing rider seat and handlebar loads, it has some limitations. Comparisons to published studies that utilized different styles of instrumented bicycle and/or different power levels show greatly varying rider load distributions. Therefore, the raw seat and handlebar load results from this study may only be applicable to similar experimental setups that utilize a stationary bicycle with moderate cycling power level.

Further limitations to this study are sample size and range of body types and participant ages tested. Increasing the number and variety of participants would likely decrease the range of statistical uncertainty in the results of this study, as well as increase the applicability of its conclusions across a wider range of participants. Some trials used in this study also contained noisy marker data that could have also contributed to the range of uncertainty in the statistical results. Finally, conclusions in this study rely solely on recommendations for maximum pelvic residual forces provided by OpenSim. These recommendations are derived from trial and error during the OpenSim development process but were not verified by this study. This study did not test how errors in the pelvic residuals effect downstream calculations, such as hip or knee joint contact loads.

Future work that may strengthen the conclusions of this study is the utilization of a full body model in OpenSim. This study relied on a simplified upper body model which did not include arms. The addition of arms to the model may increase the accuracy of the modeling. Additionally, future work could attempt to apply the seat and handlebar loads captured experimentally to the model directly. This procedure could result in more accurate results for both the pelvic residuals and joint contact loads.

REFERENCES

- [1] G. Orekhov, E. A. Heyde, A. M. Robinson, S. J. Hazelwood, and S. M. Klisch, "Asymmetry in peak ground/pedal reaction forces for transtibial amputees in gait, cycling, and elliptical training," in *World Congress of Biomechanics*, 2018.
- [2] M. V. Pottinger, "INVERSE DYNAMIC ANALYSIS OF ACL RECONSTRUCTED KNEE JOINT BIOMECHANICS," California Polytechnic State University, 2018.
- [3] J. D. Gutierrez-Franco, "THE EFFECTS OF OBESITY ON RESULTANT KNEE JOINT LOADS FOR GAIT AND CYCLING," California Polytechnic State University, 2016.
- [4] L. I. Kraemer *et al.*, "Design and implementation of an instrumented pedal for cycling biomechanics research," in *Summer Biomechanics, Bioengineering & Biotransport Conference*, 2015.
- [5] P. D. Soden and B. A. Adeyefa, "Forces Applied to a Bicycle During Normal Cycling," *J. Biomech.*, vol. 12, no. 7, pp. 527–541, 1979.
- [6] F. Bolourchi and M. L. Hull, "Measurement of rider induced loads during simulated bicycling," *Int. J. Sport Biomech.*, vol. 1, no. 4, pp. 308–329, 1985.
- [7] C. Stone and M. L. Hull, "The effect of rider weight on rider-induced loads during common cycling situations," *J. Biomech.*, vol. 28, no. 4, pp. 365–375, 1995.
- [8] C. Wilson and T. R. Bush, "Interface forces on the seat during a cycling activity," *Clin. Biomech.*, vol. 22, no. 9, pp. 1017–1023, 2007.
- [9] A. CARAHALIOS, "AN ANALYSIS OF THE BICYCLE-RIDER INTERFACE FORCES IN STATIONARY ROAD CYCLING," 2015.
- [10] J. Vanwalleghe, F. Mortier, I. De Baere, M. Loccufer, and W. Van Paepegem, "Instrumentation of a Racing Bicycle for Outdoor Field Testing and Evaluation of the Cyclist ' S Comfort Perception," pp. 1–12, 2010.

- [11] J. M. Drouet and Y. Champoux, "Development of a three-load component instrumented stem for road cycling," *Procedia Eng.*, vol. 34, pp. 502–507, 2012.
- [12] J. Vanwallegem, I. De Baere, M. Loccufier, and W. Van Paepegem, "Dynamic calibration of a strain gauge based handlebar force sensor for cycling purposes," *Procedia Eng.*, vol. 112, pp. 219–224, 2015.
- [13] D. D. D'Lima, N. Steklov, S. Patil, and C. W. Colwell, "The Mark Coventry Award: in vivo knee forces during recreation and exercise after knee arthroplasty," *Clin. Orthop. Relat. Res.*, vol. 466, no. 11, pp. 2605–2611, 2008.
- [14] I. Kutzner *et al.*, "Loading of the Knee Joint During Ergometer Cycling: Telemetric In Vivo Data," *J. Orthop. Sport. Phys. Ther.*, vol. 42, no. 12, pp. 1032–1038, 2012.
- [15] R. R. Neptune and S. A. Kautz, "Knee joint loading in forward versus backward pedaling: Implications for rehabilitation strategies," *Clin. Biomech.*, vol. 15, no. 7, pp. 528–535, 2000.
- [16] M. O. Ericson and R. Nisell, "Tibiofemoral joint forces during ergometer cycling," *Am J Sport. Med.*, vol. 14, no. 4, pp. 285–290, 1986.
- [17] S. L. Delp *et al.*, "OpenSim: open-source software to create and analyze dynamic simulations of movement," *Biomed. Eng. IEEE Trans.*, vol. 54, no. 11, pp. 1940–1950, 2007.
- [18] B. A. Knarr and J. S. Higginson, "The ability of the residual reduction algorithm to account for handrail use during gait analysis," in *ASME 2012 Summer Bioengineering Conference*, 2012, pp. 1059–1060.
- [19] "LifeCycle GX Training Manual." Life Fitness, 2014.
- [20] K. Dudum, "Placing markers in accordance with enhanced helen hayes." Human Motion Biomechanics Lab Standard Operation Procedure, 2015.

- [21] G. Orekhov, "HIP AND KNEE BIOMECHANICS FOR TRANSTIBIAL AMPUTEES IN GAIT, CYCLING, AND ELLIPTICAL TRAINING," California Polytechnic State University, 2018.
- [22] S. L. Delp, J. P. Loan, M. G. Hoy, F. E. Zajac, E. L. Topp, and J. M. Rosen, "An interactive graphics-based model of the lower extremity to study orthopedic surgical procedures," *IEEE Trans. Biomed. Eng.*, vol. 37, no. 8, pp. 757–767, 1990.
- [23] A. K. M. Lai, A. S. Arnold, and J. M. Wakeling, "Why are Antagonist Muscles Co-activated in My Simulation? A Musculoskeletal Model for Analysing Human Locomotor Tasks," *Ann. Biomed. Eng.*, vol. 45, no. 12, pp. 2762–2774, 2017.
- [24] "How RRA Works," *Stanford University*. [Online]. Available: <https://simtk-confluence.stanford.edu/display/OpenSim/How+RRA+Works>.

Appendix A. Hand Drawings of Preliminary Design Concepts

③ version of ② for seat

use block with rod for attaching seat instead.

would have to grind old seat rod off.

- Invasive (would have to modify bike or get new pieces)
- Less machining

④

splice seat post and weld in plates to attach to transducer.

- Invasive
- only for seat
- Minimal material needs
- would require welding
- could effect seat position if welded incorrectly

Appendix B. Detail Drawings of Bicycle Instrumentation Components

Provided in this appendix are detail drawings of the parts used to instrument the handlebar and seat post of a stationary exercise bicycle with AMTI load cells. All parts were fabricated from 6061 aluminum although the specific allow used is not critical. Parts could also be manufactured from steel or another high strength material. Parts are named based on type (P for plate and B for bracket) and then sequentially starting from 1. Assembly drawings for the seat and handlebar assemblies are also reproduced at the end of this appendix. Further information and design considerations can be found in the methods section of the main body of this thesis. Figures B.1 and B.2 show exploded views for the seat and handlebar instrumentation assembly.

Figure B.1: Exploded view of bike seat instrumentation design.

Figure B.2: Exploded view of bike handlebar instrumentation design.

- NOTES
1. MATERIAL: ALUMINUM
 2. THICKNESS: .25 INCHES
 3. ALL DIMENSIONS IN INCHES
 4. TOLERANCES: X.XX = ±.01
 5. BREAK CORNERS AS NEEDED

Scale 1:1

Bike Mod Drawing # 001

Seat Plate: P1

02/12/2019

Brad Wash

- NOTES
1. MATERIAL: ALUMINUM
 2. THICKNESS: .25 INCHES
 3. ALL DIMENSIONS IN INCHES
 4. TOLERANCES: X.XX = $\pm .01$
 5. BREAK CORNERS AS NEEDED

Scale 1:1

Bike Mod Drawing # 002		
Seat Plate: P2	02/12/2019	Brad Wash

- NOTES
1. MATERIAL: ALUMINUM
 2. ALL DIMENSIONS IN INCHES
 3. TOLERANCES: X.XX $\pm$.01
 4. BREAK CORNERS AS NEEDED

Scale 1:1

Bike Mod Drawing # 003

Handle Bracket: B1

02/12/2019

Brad Wash

NOTES

1. MATERIAL: ALUMINUM
2. ALL DIMENSIONS IN INCHES
3. TOLERANCES: X.XX = $\pm .01$
4. BREAK CORNERS AS NEEDED

Handle Bracket: B1

Brad Wash

Brad Wash

Appendix C. Load Cell Calibration Check Results

In order to check the accuracy of the load cells in their as mounted positions on the bike, several calibration checks were performed. All of these checks utilized exercise weights either on their own placed atop the load cells or along with the calibration frame to apply known loading to the force transducers. The general strategy was to then check the output of the transducers against this known load to confirm proper calibration.

Check 1:

Check 1 was the first and most simplistic method used to gather some baseline information on the seat load cell performance. Loads were applied one at a time in a single direction, except for when intending to apply a moment when a force in the complimentary direction was also present. The results for this test showed reliable transducer response and are given in the following figures.

Figure C.1: Initial force check in anterior-posterior direction.

Figure C.2: Initial force check in medial-lateral direction.

Figure C.3: Initial force check in superior-inferior direction.

Figure C.4: Initial moment check in anterior-posterior direction.

Figure C.5: Initial moment check in medial-lateral direction.

Having established that the seat force transducer was behaving as expected with a single load, further testing was required to show that the load cells could properly measure complex loading.

Check 2:

Testing for this case was accomplished by the addition of an extruded aluminum frame which allowed the point of load application to be moved away from the load cell itself. This made it possible to apply three known forces and three known moments simultaneously. The results for this test were mixed and are shown in the figures below. Also shown in Figure C.6 is an image of the testing apparatus.

Figure C.6: Testing apparatus for Check 2. The calibration frame can be seen on the left, the aluminum frame is on the seat post, and markers show up as white dots.

Figure C.7: Complex calibration check force results in anterior-posterior direction.

Figure C.8: Complex calibration check force results in medial-lateral direction.

Figure C.9: Complex calibration check force results in superior-inferior direction.

Figure C.10: Complex calibration check moment results in anterior-posterior direction.

Figure C.11: Complex calibration check moment results in medial-lateral direction.

Figure C.12: Complex calibration check moment results in superior-inferior direction.

These results showed reasonable moment responses for both load cells but poor force responses, especially in the superior-inferior direction. These results did not agree with those of the initial calibration check or with data obtained from preliminary rider testing, all of which showed reasonable values close to literature. It was concluded that the relatively high moments were causing inaccuracies in the force readings. This is a reasonable conclusion but in order to obtain further validation, a third test was designed in which loads were applied to the force transducers in proportion to those seen in actual cycling.

Check 3:

The data for the three test cases that comprised check 3 and their results are shown in the following table and figures.

Table C.1: Typical seat loads and calibration check test cases.

	Anterior-Posterior	Superior-Inferior	Medial-Lateral
	Force [N]	Force [N]	Moment [Nm]
Typical Loads	80.0	-500.0	-25.0
Trial 1	23.1	-215.8	-7.3
Trial 2	57.4	-409.6	-18.1
Trial 3	91.2	-619.5	-28.9

Table C.2: Typical handlebar loads and calibration check test cases.

	Anterior-Posterior	Superior-Inferior	Medial-Lateral
	Force [N]	Force [N]	Moment [Nm]
Typical Loads	-100.0	-100.0	10.0
Trial 1	-22.1	-22.6	2.5
Trial 2	-44.6	-44.8	5.1
Trial 3	-161.3	-166.6	18.3

Figure C.13: Seat anterior-posterior force calibration check results.

Figure C.14: Seat superior-inferior force calibration check results.

Figure C.15: Seat medial-lateral moment calibration check results.

Figure C.16: Handlebar anterior-posterior force calibration check results.

Figure C.17: Handlebar superior-inferior force calibration check results.

Figure C.18: Handlebar medial-lateral moment calibration check results.

The results from the proportional calibration check show, with a reasonable amount of certainty, that under typical cycling conditions, the load cells are capable of producing accurate readings.

Appendix D. Plots of Knee Loads, LaiArnold vs. Gait 2392

Provided in this appendix is a comparison of the OpenSim Joint Reaction results from the LaiArnold model and the Gait 2392 model. Specifically shown below are plots for knee joint forces and moments from one cycle of cycling for a 49.6 kg or 487 N participant pedaling at a moderate resistance level and 70 RPM. The axis are defined with respect to the rider as positive forward (anterior), left (lateral), and up (superior). The choice of OpenSim model clearly has a large effect on the results of a given experiment and could thus be considered the most important modeling decision. Both peak values and plot shape vary greatly between the Gait 2392 and LaiArnold model. Published work on cycling tends to indicate that knee compression forces are roughly equal to body weight and anterior-posterior shearing forces are low compared to body weight. These results are consistent with peak values produced using the LaiArnold model which is good evidence to support its superiority over Gait 2392 in modeling cycling.

Figure D.1: Knee anterior-posterior shear force results from Gait 2392 and LaiArnold models.

Figure D.2: Knee medial-lateral shear force results from Gait 2392 and LaiArnold models.

Figure D.3: Knee superior-inferior compression force results from Gait 2392 and LaiArnold models.

Figure D.4: Knee anterior-posterior moment results from Gait 2392 and LaiArnold models.

Figure D.5: Knee medial-lateral moment results from Gait 2392 and LaiArnold models.

Figure D.6: Knee superior-inferior moment results from Gait 2392 and LaiArnold models.

Appendix E. Plots of Knee Loads, All Participants

Provided in this appendix are plots showing the OpenSim Joint Reaction results for right knee loading in all five subjects. Results were generated using the LaiArnold high flexion model. Two plots are provided for each force and moment direction. The first plot shows a five cycle average for each trial and the second plot shows an average of those trials per participant. This is done to give the reader an idea of how the data vary between trials. Note that the results have greater variation between participants than within participant trials. This is expected as bicycle ergonomics and individual body types have a large effect on the resulting kinetics. For example, participant 2018July13-01 (labeled July13) cycled with the seat set farther forward than is typical. This resulted in a distinctly different knee load distribution compared to the other participants. Axes are defined as positive right, forward, and up with respect to the tibia. These results were not rigorously compared to the published literature. However, comparisons of peak knee forces to published data shown in Table E.1 shows reasonable agreement.

Table E.1: Summary of published results on peak knee loading during cycling.

Study	Peak S-I Compression Force [N/N]	Peak A-P Shear Force [N/N]
D'Lima et al. [13]	1.03±0.20	0.21±0.01
Kutzner et al. [14]	1.19	0.05-0.07
Neptune and Kantz [15]	1.8	2.1
Ericson and Nisell [16]	1.2	0.055

Figure E.1: Normalized knee anterior-posterior force averaged across five cycles for each trial.

Figure E.2: Normalized knee anterior-posterior force averaged across five cycles and three trials for each participant.

Figure E.3: Normalized knee medial-lateral force averaged across five cycles for each trial.

Figure E.4: Normalized knee medial-lateral force averaged across five cycles and three trials for each participant.

Figure E.5: Normalized knee superior-inferior force averaged across five cycles for each trial.

Figure E.6: Normalized knee superior-inferior force averaged across five cycles and three trials for each participant.

Figure E.7: Normalized knee anterior-posterior moment averaged across five cycles for each trial.

Figure E.8: Normalized knee anterior-posterior moment averaged across five cycles and three trials for each participant.

Figure E.9: Normalized knee medial-lateral moment averaged across five cycles for each trial.

Figure E.10: Normalized knee medial-lateral moment averaged across five cycles and three trials for each participant.

Figure E.11: Normalized knee superior-inferior moment averaged across five cycles for each trial.

Figure E.12: Normalized knee superior-inferior moment averaged across five cycles and three trials for each participant.

Appendix F. MatLab Code

Provided in this appendix is the primary MatLab code used to process the raw data in this study. The primary roll of this code is to intake the large quantity of numerical data collected, perform necessary coordinate transformations, calculate the HBSE loads, and plot them versus the results from OpenSim's RRA. This code does not perform any statistical analysis on these results and does not contain any novel work in and of itself. Similar processing could easily be done by hand or in other programs such as Microsoft Excel, although doing so for every trial would be significantly more time consuming. Additionally, the MatLab language is not specifically required to perform this type of analysis. In addition to the main code, a function for finding the crank angle of the bicycle pedals for each frame in time is provided. This function is called by the main code and could easily be integrated into it but has been left separate as a standalone function because it proved to be useful in other applications.

Contents

- [House keeping and User Prompt](#)
- [Load in force/moment data from .anp](#)
- [Load in position data from .ts and .trc](#)
- [Load in OpenSim RRA Results](#)
- [Calculate Pelvic Residual](#)
- [Stats Setup](#)
- [Plot Results](#)
- [Close Files](#)

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Script for analyzing the pelvic residual force on stationary
% bicycle rider.
%
% Updates:
%
% V2 - added OpenSim ID results as inputs in order to output plots
%      that directly compare measured data to OpenSim residuals.
%
% V3 - added correction for different time step in post rra ID results
%
% V4 - Added cycle capability and user input to select cycle of interest
%      Added plots of resultant loads as well as components
%
% V5 - Changed outputs to local coordinates via transformation matrices
%
% V6 - Added sections for compiling stats information. Removed mentions
%      to Inverse Dynamics (no longer used for comparing RRA results)
%
% inputs:
% *processed.anp file containing force data for seat and handlebars
% *Forces.anp file containing tare data for seat and handlebars
% *procesed.trc file containing location of pelvic center
% *Forces.trc file containing locations of force transducers
% *original.sto file containing OpenSim ID results pre RRA
% *RRA.sto file containing OpenSim ID results post RRA
%
% Required Functions:
%   Crank_Angle.m
%
% This script is designed to work with a specific set of input files and
% workflow. When generating experimental data from the fully instrumented
% bike, ensure that there are at least two seconds of capture data at the
% beginning of the trial in which the subject is not sitting on or near the
% bike. When post processing, generate two sets of processed files. The
% first set is named subjectID_Forces and is responsible for taring the
% forces and setting the location of the centers of the force transducers.
% Process these data using the BikeForces markerset and save the trimmed
% file with the identifying lable of *****_Forces. The other set of
% processed files is done in the typical way in preparation for opensim.
% This script will input two files from each set. It will find the force
% transducer electrical origin by reading the subjectID_Forces.trc file and
% gather tare data by reading the subjectID_Forces.anp file. The remainder
% of the data comes from the subjectID_processed.anp file generated by the
```

```

% normal post processing procedure. The last set of information is the xyz
% location of the pelvic center. This .trc file is also automatically
% generated from the normal post processing procedure
%
% To run this script, simply place this MatLab file and its required
% functions in a folder with and only with the necessary input files,
% open it up in MatLab and run the program.
% You will be prompted to set the directory folder and input a
% cycle of interest. No physical modification of the code body is necessary
% to run the script successfully.
%
% This script will automatically generate plots of its outputs but if the
% raw data are needed as well, it can be taken manually from the variables
% Pelvic_Forces and Pelvic_Moments and copied into another location such
% as Microsoft Excel
%
% **All results are numerically in local body Coordinates**
% X is anterior-posterior, positive forward
% Y is superior-inferior, positive up
% Z is medial-lateral, positive right
%
% Note on textscan function:
% This script relies on the textscan function for all of its file reading.
% The code used is adapted from Greg O's cortex to opensim code and is
% very easy to implement. If you are looking to create an m file of your
% own that needs to read any of the cortex files, use the following chunk
% of code.
% d = dir('filename.file_extention'); <-- enter actual filename here
% file = {d.name}; <-- name "file" whatever you want
% fid = fopen(string(file));
% A = textscan(fid, repmat('%s',[1,#]), 'Headerlines', #, 'Delimiter', '\t');
%           |           |
%           Change to num of columns   change to num of headerlines
%
% You can then use normal cell operations to extract the values you want
%
%
% Human Motion Biomechanics Lab
% California Polytechnic State University, SLO
% Brad Wash
% bradwash@gmail.com
% 06/28/2018
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

House keeping and User Prompt

```

clear

%create popup to prompt user for a cycle of interest
prompt = {'Start Cycle'}; % title of the user input field
title = 'Enter Cycle to Plot (e.g. 1 for first cycle)'; % prompt title
dims = [1 90];
%answer = {'1'}; % default answers used to suppress prompt during debugging
answer = inputdlg(prompt,title,dims); %execute prompt

```

```
Start_Cycle = str2double(answer{1,1}); %convert user input to useable number
```

Load in force/moment data from .anp

Load initial data for taring load cells

```
d = dir('*Forces.anp'); %grab anp file name that ends with 'Forces'
anp_zero_name = {d.name}; %save exact filename
fid = fopen(string(anp_zero_name)); %open file
% The following function reads the cortex file and puts the results into a
% 1xn array of cells. Each cell then contains all of the data in that
% column of the file.
% read file- file ID,49 sting entities,ignore file header,tab delimited
A = textscan(fid, repmat('%s',[1,49]), 'Headerlines',10, 'Delimiter', '\t');

for i = 1:size(A,2) % this section accounts for the random
    str = string(A{1,i}{1,1}); % order of apearence of load cells in
    if str == "F7X (Processed)" % the .anp file by scanning for the
        S = i; % correct seat/handle force column label
    end % seat is always F7, handle is F8
    if str == "F8X (Processed)"
        H = i;
    end
end

% unpack the cells into normal matrix of doubles using the index from above
Seat_Zero_Forces = str2double([A{1,S}, A{1,S+1}, A{1,S+2}]);
Seat_Zero_Forces(1,:) = []; % delete the header line
Seat_Zero_Moments = str2double([A{1,S+3}, A{1,S+4}, A{1,S+5}]);
Seat_Zero_Moments(1,:) = []; % delete the header line

Handle_Zero_Forces = str2double([A{1,H}, A{1,H+1}, A{1,H+2}]);
Handle_Zero_Forces(1,:) = []; % delete the header line
Handle_Zero_Moments = str2double([A{1,H+3}, A{1,H+4}, A{1,H+5}]);
Handle_Zero_Moments(1,:) = []; % delete the header line

% Load in trial data
% this section begins with the same operational code as the last
d = dir('*processed.anp'); %grab anp file name that ends with 'processed'
anp_processed_name = {d.name}; %save filename
fid = fopen(string(anp_processed_name));
% read file 49 sting entities ignore file header tab delimited
B = textscan(fid, repmat('%s',[1,49]), 'Headerlines',10, 'Delimiter', '\t');

% The same indexes S and H are reused for this section without rescanning.
% This is because the transducer order does not change between multiple
% files trimmed from the same original capture
Seat_Raw_Forces = str2double([B{1,S}, B{1,S+1}, B{1,S+2}]);
Seat_Raw_Forces(1,:) = [];
Seat_Raw_Moments = str2double([B{1,S+3}, B{1,S+4}, B{1,S+5}]);
Seat_Raw_Moments(1,:) = [];

Handle_Raw_Forces = str2double([B{1,H}, B{1,H+1}, B{1,H+2}]);
Handle_Raw_Forces(1,:) = [];
```

```

Handle_Raw_Moments = str2double([B{1,H+3},B{1,H+4},B{1,H+5}]);
Handle_Raw_Moments(1,:) = [];

% Tare force and moment data
% The raw forces are subtracted by the average of the zero forces
Seat_Forces = Seat_Raw_Forces - ...
    sum(Seat_Zero_Forces)/size(Seat_Zero_Forces,1);
Seat_Moments = Seat_Raw_Moments - ...
    sum(Seat_Zero_Moments)/size(Seat_Zero_Moments,1);

Handle_Forces = Handle_Raw_Forces - ...
    sum(Handle_Zero_Forces)/size(Handle_Zero_Forces,1);
Handle_Moments = Handle_Raw_Moments - ...
    sum(Handle_Zero_Moments)/size(Handle_Zero_Moments,1);

```

Load in position data from .ts and .trc

Load in pelvic origin same structure as previous

```

d = dir('*rocessed.trc');
trcp_name = {d.name};
fid = fopen(string(trcp_name));
C = textscan(fid, repmat('%s',[1,203]), 'Headerlines',3, 'Delimiter', '\t');

for i = 1:size(C,2) % this section searches through the
    str = string(C{1,i}{1,1}); % trc file and finds the correct
    if str == "V_Pelvis-Origin" % header for the pelvic origin
        J = i; % marker
    end
end

% the .trc file does not vary in its contents so indexes are not needed
% however its good practice to verify
Pelvic_XYZ = str2double([C{1,J},C{1,J+1},C{1,J+2}]);
Pelvic_XYZ(1:2,:) = [];
Frame_Time = str2double([C{1,1},C{1,2}]);
Frame_Time(1:2,:) = [];

% check for any unprocessed spots in the trc file
if any(isnan(Pelvic_XYZ)) == 1
    error('Error: Pelvic Origin Marker Data Not Fully Processed')
end

% Find Cycle Times and angles
[R_crank_angle,L_crank_angle,R_TDC,L_TDC] = Crank_Angle(C);

% Load in load cell positions
% same structure as previous
d = dir('*orces.trc'); % exclude the f in forces to make case insensitive
trcf_name = {d.name};
fid = fopen(string(trcf_name));
D = textscan(fid, repmat('%s',[1,20]), 'Headerlines',6, 'Delimiter', '\t');

% the forces.trc does not vary and is exclusive to this codes processing
FT_Markers = str2double([D{1,3},D{1,4},D{1,5},D{1,6},D{1,7},D{1,8},...

```

```

D{1,9},D{1,10},D{1,11},D{1,12},D{1,13},D{1,14},D{1,15},D{1,16},...
D{1,17},D{1,18},D{1,19},D{1,20}]);

E = sum(FT_Markers)/size(FT_Markers,1); % find the average xyz positions

% find and save average xyz locations of load cell electrical origins
Handle_XYZ = [(E(4)+E(7))/2, (E(5)+E(8))/2, (E(3)+E(6)+E(9))/3];
Seat_XYZ = [(E(13)+E(16))/2, (E(14)+E(17))/2, ...
(E(12)+E(15)+E(18))/3];

% check for missing data
if any(isnan(Handle_XYZ))==1 || any(isnan(Seat_XYZ))==1
    error('Error: Handle/Seat Marker Data Not Fully Processed')
end

```

Load in OpenSim RRA Results

```

% same structure as previous
d = dir('*orce.sto');
rraF_name = {d.name};
fid = fopen(string(rraF_name));
G = textscan(fid, repmat('%s',[1,22]), 'Headerlines',23, 'Delimiter', '\t');

% the .sto file does not vary in its contents so indexes are not needed
rra_Time = str2double(G{1,1});
Pelvic_Forces_rraF = str2double([G{1,2},G{1,3},G{1,4}]);
Pelvic_Moments_rraF = str2double([G{1,5},G{1,6},G{1,7}]);

%Root Sum Square forces to get total resultant force for plotting
Pelvic_RF_rraF = ( (Pelvic_Forces_rraF(:,1).^2) + ...
(Pelvic_Forces_rraF(:,2).^2) + (Pelvic_Forces_rraF(:,3).^2) ).^(1/2);
Pelvic_RM_rraF = ( (Pelvic_Moments_rraF(:,1).^2) + ...
(Pelvic_Moments_rraF(:,2).^2) + (Pelvic_Moments_rraF(:,3).^2) ).^(1/2);

```

Calculate Pelvic Residual

```

if Start_Cycle > length(R_TDC) % throw error if user input is too large
    error('Start cycle outside of range')
end

% lookup start and stop frame from the right foot top dead center list
Low_Frame = R_TDC(Start_Cycle,1);
High_Frame = R_TDC(Start_Cycle+1,1)-1;

% Find correct rra start and finish frames
% This lookup is necessary because rra uses a different time increment
for i = 1:size(rra_Time,1)
    if R_TDC(Start_Cycle,2) == round(rra_Time(i),3)
        Low_rra_Frame = i; % ^ round to three decimal places
    end
end

for i = 1:size(rra_Time,1)
    if R_TDC(Start_Cycle+1,2) == round(rra_Time(i),3)
        High_rra_Frame = i;
    end
end

```

```

% this line creates an evenly spaced vector for rra crank angle
% this assumes a constant angular velocity throughout the cycle which
% is a good enough assumption for graphical presentation of data
rra_angle = linspace(0,360,High_rra_Frame-Low_rra_Frame+1);

% Find rotation offset of bike in room
theta = atan((Handle_XYZ(1)-Seat_XYZ(1))/(Handle_XYZ(2)-Seat_XYZ(2)));

% Set up transformation matrices
T_ls = [ 0      1      0      ; ... % Transformation matrix
        0      0     -1      ; ... % Load Cell to local
        -1      0      0      ];

T_rm = [-sin(theta) -cos(theta)  0      ; ... % Transformation matrix
        0      0      1      ; ... % Room/Cortex to local
        -cos(theta) sin(theta)  0      ];

T_os = [-sin(theta)  0      cos(theta) ; ... % Transformation matrix
        0      1      0      ; ... % OpenSim to local
        -cos(theta)  0     -sin(theta) ];

% Transform all data into local coordinates
% This is done in different groups depending on array size but is
% essentially all done in the same way
Handle_XYZ = (T_rm*Handle_XYZ)'; % Single point transforms
Seat_XYZ = (T_rm*Seat_XYZ)';

for i = 1:size(Frame_Time,1) % Multi point raw data
    Seat_Forces(i,:) = (T_ls*Seat_Forces(i,:))';
    Handle_Forces(i,:) = (T_ls*Handle_Forces(i,:))';
    Seat_Moments(i,:) = (T_ls*Seat_Moments(i,:))';
    Handle_Moments(i,:) = (T_ls*Handle_Moments(i,:))';
    Pelvic_XYZ(i,:) = (T_rm*Pelvic_XYZ(i,:))';
end

for i = 1:size(Pelvic_Forces_rraF,1) % Multi point OpenSim post RRA
    Pelvic_Forces_rraF(i,:) = -(T_os*Pelvic_Forces_rraF(i,:))';
    Pelvic_Moments_rraF(i,:) = -(T_os*Pelvic_Moments_rraF(i,:))';
end

% Calculate Residuals
Pelvic_Forces = zeros(size(Frame_Time,1), 3); % pre allocate matrix
Pelvic_Moments = zeros(size(Frame_Time,1), 3);
r_Seat = zeros(size(Frame_Time,1), 3);
r_Handle = zeros(size(Frame_Time,1), 3);

for i = 1:size(Frame_Time,1)
    n = i; % -Low_Frame+1; % create index starting from 1 to use in loop

    Fxyz = Seat_Forces(i,:) + Handle_Forces(i,:); % sum F

    % these three lines calculate the resultant moments by adding the
    % two free moments with the four additional force/lever moments
    r_Seat(n,:) = (Seat_XYZ - Pelvic_XYZ(i,:))/1000; % seat lever
    r_Handle(n,:) = (Handle_XYZ - Pelvic_XYZ(i,:))/1000; % handle lever
end

```



```

Mxyz = Seat_Moments(i,:) + Handle_Moments(i,:) + ... % sum M
cross(r_Seat(n,:), Seat_Forces(i,:)) + ...
cross(r_Handle(n,:), Handle_Forces(i,:));

% create matrices for pelvic residual forces and moments
% values are inverted to give bike on pelvis instead of pelvis on
% bike which is what the load cells measure
Pelvic_Forces(n,:) = [-Fxyz(1),-Fxyz(2),-Fxyz(3)];
Pelvic_Moments(n,:) = [-Mxyz(1),-Mxyz(2),-Mxyz(3)];

end

% Root Sum Square to get single reaction force and moment
Pelvic_RF = ( (Pelvic_Forces(:,1).^2) + ...
(Pelvic_Forces(:,2).^2) + (Pelvic_Forces(:,3).^2) ).^(1/2);
Pelvic_RM = ( (Pelvic_Moments(:,1).^2) + ...
(Pelvic_Moments(:,2).^2) + (Pelvic_Moments(:,3).^2) ).^(1/2);

```

Stats Setup

This section compiles some data together in a way that is easy to copy and paste into excel for stats analysis. The format may or may not be useful for future users.

```

%Line up RRA results with Experimental Results
j = 1;
Pelvic_RF_rra_short = zeros(size(Frame_Time, 1),2); % pre allocate
Pelvic_Loads_rraF_short = zeros(size(Frame_Time, 1),6);
for i = 1:size(rra_Time)
    if rra_Time(i) == Frame_Time(j,2) % parcel out aligning frames
        Pelvic_RF_rra_short(j,:) = [rra_Time(i),Pelvic_RF_rraF(i)];
        Pelvic_Loads_rraF_short(j,:) = ...
            [Pelvic_Forces_rraF(i,:), Pelvic_Moments_rraF(i,:)];
        j = j+1; % increment index
    end
end

range = 4; % set number of cycles to output
% Set up a matrix that contains rra and experimental resultant force
% results over the same crank angles
RMSE_Stats = [R_crank_angle(R_TDC(1,1):R_TDC(range+1,1)-1,1), ...
    Pelvic_RF_rra_short(R_TDC(1,1):R_TDC(range+1,1)-1,2), ...
    Pelvic_RF(R_TDC(1,1):R_TDC(range+1,1)-1,1)];
% Set up a matrix that contains rra and experimental load results over
% the same crank angles
Stats = [R_crank_angle(R_TDC(1,1):R_TDC(range+1,1)-1,1), ...
    Pelvic_Loads_rraF_short(R_TDC(1,1):R_TDC(range+1,1)-1,:), ...
    Pelvic_Forces(R_TDC(1,1):R_TDC(range+1,1)-1,:), ...
    Pelvic_Moments(R_TDC(1,1):R_TDC(range+1,1)-1,:)];

```

Plot Results

this section generates all of the output plots components and resultants are grouped into different subplots

```

l = Low_Frame; % shortening for plot inputs
h = High_Frame;
rl = Low_rra_Frame;
rh = High_rra_Frame;

% Plots of component forces and moments
figure
subplot(2,3,1)
clear title xlabel ylabel
plot(R_crank_angle(1:h,1), Pelvic_Forces(1:h,1), ...
     rra_angle(), Pelvic_Forces_rraF(rl:rh,1));
title('Pelvic Residual Anterior-Posterior Force');
xlabel('Crank Angle [degrees]');
ylabel('Force [N]');
legend('Measured','OS RRA');

subplot(2,3,2)
plot(R_crank_angle(1:h,1), Pelvic_Forces(1:h,2), ...
     rra_angle(), Pelvic_Forces_rraF(rl:rh,2));
title('Pelvic Residual Superior-Inferior Force');
xlabel('Crank Angle [degrees]');
ylabel('Force [N]');
%legend('Measured','OS RRA');

subplot(2,3,3)
plot(R_crank_angle(1:h,1), Pelvic_Forces(1:h,3), ...
     rra_angle(), Pelvic_Forces_rraF(rl:rh,3));
title('Pelvic Residual Medial-Lateral Forces');
xlabel('Crank Angle [degrees]');
ylabel('Moment [Nm]');
%legend('Measured','OS RRA');

subplot(2,3,4)
plot(R_crank_angle(1:h,1), Pelvic_Moments(1:h,1), ...
     rra_angle(), Pelvic_Moments_rraF(rl:rh,1));
title('Pelvic Residual Anterior-Posterior Moments');
xlabel('Crank Angle [degrees]');
ylabel('Moment [Nm]');
%legend('Measured','OS RRA');

subplot(2,3,5)
plot(R_crank_angle(1:h,1), Pelvic_Moments(1:h,2), ...
     rra_angle(), Pelvic_Moments_rraF(rl:rh,2));
title('Pelvic Residual Superior-Inferior Moments');
xlabel('Crank Angle [degrees]');
ylabel('Moment [Nm]');
%legend('Measured','OS RRA');

subplot(2,3,6)
plot(R_crank_angle(1:h,1), Pelvic_Moments(1:h,3), ...
     rra_angle(), Pelvic_Moments_rraF(rl:rh,3));
title('Pelvic Residual Medial-Lateral Moments');
xlabel('Crank Angle [degrees]');
ylabel('Moment [Nm]');

```

```

%legend('Measured','OS RRA');

% Plots of resultant forces and moments
figure
subplot(1,2,1)
plot(R_crank_angle(1:h,1), Pelvic_RF(1:h,1), ...
    rra_angle(), Pelvic_RF_rraF(rl:rh,1));
title('Pelvic Resultant Force');
xlabel('Crank Angle [degrees]');
ylabel('Force [N]');
legend('Measured','OS RRA');

subplot(1,2,2)
plot(R_crank_angle(1:h,1), Pelvic_RM(1:h,1), ...
    rra_angle(), Pelvic_RM_rraF(rl:rh,1));
title('Pelvic Resultant Moment');
xlabel('Crank Angle [degrees]');
ylabel('Moment [Nm]');
legend('Measured','OS RRA');

```

Close Files

```
fclose('all');
```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Script for finding the crank angle of a stationary
% bicycle pedal.
%
% This script as is has a discontinuity in the first derivative when
% transitioning through 180 degrees. Position data is reasonably reliable but
% velocity derived from position will likely have issues. This issue is
% something to do with the inverse tangent angle calculation
%
% Inputs:
%   Cell array containing all the data in a .trc file
%
% Example of Code to Read .trc and call function
% d = dir('*.*trc');
% trc_name = {d.name};
% fid = fopen(string(trc_name));
% A = textscan(fid, repmat('%s',[1,203]), 'Headerlines', 3, 'Delimiter', 't');
% [R_crank_angle, L_crank_angle, R_TDC, L_TDC] = Crank_Angle(A);
%
% Outputs:
%   Vector containing right leg crank angles for all time
%   Vector containing left leg crank angles for all time
%   Vector containing frame and times of right leg top dead center
%   Vector containing frame and times of left leg top dead center
%
% Human Motion Biomechanics Lab
% California Polytechnic State University, SLO
% Brad Wash
% bradwash@gmail.com
% 06/28/2018
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [R_crank_angle, L_crank_angle, R_TDC, L_TDC] = Crank_Angle(A)

for i = 1:size(A,2)          % this section searches through the
    str = string(A{1,i}{1,1}); % trc file and finds the correct
    if str == "L.Spindle"     % header for the left spindle
        S = i;               % marker
    end
    if str == "R.Spindle"
        H = i;
    end
end

% unpack the cells into normal matrix of doubles using the index from above
L_crank_xyz = str2double([A{1,S}, A{1,S+1}, A{1,S+2}]);
L_crank_xyz(1:2,:) = []; % delete the header line
R_crank_xyz = str2double([A{1,H}, A{1,H+1}, A{1,H+2}]);
R_crank_xyz(1:2,:) = [];
Times = str2double([A{1,2}]);
Times(1:2,:) = [];

[R_crank_angle, R_TDC] = angle(R_crank_xyz, Times); % call internal Fn
[L_crank_angle, L_TDC] = angle(L_crank_xyz, Times);

```

```

% Function for exicuting all the calculations
function [crank_angle, TDC] = angle(spindle, time)

[~, top_fn] = findpeaks(spindle(:,3)); % finds when pedal is at top
[~, bottom_fn] = findpeaks(-spindle(:,3)); % and when pedal is on bottom
% Calculate an average center of rotation for the crank
center_xyz = (sum(spindle(top_fn,:))/length(top_fn) ...
    + sum(spindle(bottom_fn,:))/length(bottom_fn))/2;

for i = 1:size(spindle,1)
    r_xyz = spindle(i,:) - center_xyz; % crank vector
    s = r_xyz(2)/abs(r_xyz(2)); % create a variable for direction
    % Convert the 3d rotation to a 2d rotation
    r_xz(i,:) = [s*sqrt((r_xyz(1)^2)+(r_xyz(2)^2)), r_xyz(3)];
    % Calculate the crank angle using atan2
    crank_angle(i,:) = -atan2d(r_xz(i,1),r_xz(i,2)) ...
        + 360*(r_xz(i,1)>0) ;
end

% figure
% scatter(r_xz(:,1), r_xz(:,2), 2, 'filled');
% pbaspect([1 1 1]);
% figure
% scatter(Times, crank_angle, 5, 'filled')
[~, tdc] = findpeaks(-crank_angle);
TDC = [tdc, time(tdc)];

end

end

```

Appendix G. Results from Statistical Analysis

This appendix contains the raw outputs from the statistical model. In order to simplify the statistical mode, only the peak values for each cycle were compared. This was a reasonable simplification because peak values are usually of the most concern when studying forces and moments in biomechanics. Data for each force and moment direction were arranged by participant, trial, cycle, and label (RRA vs HBSE). Significance between both label and cycle were tested. Significance between labels indicated that there was a significant difference between the peak RRA values and the Peak HBSE values. Data were analyzed using a mixed model with repeated measures in SAS. Cycle correlations were accounted for using a first order autoregressive correlation structure. In addition to a test for significance, a 95% confidence interval for the difference between RRA and HBSE peak values was developed. The short hand used to describe the force and moment directions is shown in Table G.1 and an example of the code required to run the statistics in SAS is provided for below in Figure G.1.

Table G.1: Shorthand names for peak loads.

Load	Short Hand
Peak Anterior-Posterior Force	pFx
Peak Medial-Lateral Force	pFz
Peak Superior-Inferior Force	pFy
Peak Anterior-Posterior Moment	pMx
Peak Medial-Lateral Moment	pMz
Peak Superior-Inferior Moment	pMy

```

PROC IMPORT OUT= WORK.PEAK_STATS_BW_SHEET1
  DATAFILE= " \Peak_Stats_BW.xlsx" DBMS=EXCEL REPLACE;
  RANGE="Sheet1$";
  GETNAMES=YES;
  MIXED=NO;
  SCANTEXT=YES;
  USEDATE=YES;
  SCANTIME=YES;
RUN;

PROC MIXED ASYCOV NOBOUND DATA=Peak_Stats_BW_Sheet1
  ALPHA=0.05;
  CLASS Person Trial Cycle Label;
  MODEL pFx = Cycle Label Cycle*Label/ SOLUTION
  DDFM=KENWARDROGER;
  RANDOM Trial(Person Label) Person / SOLUTION ;
  REPEATED Cycle /subject=Trial(Person Label) type=ar(1);
  LSMEANS Cycle Label/ DIFF CL;
RUN;

```

Figure G.1: Example of code ran in SAS to conduct statistical analysis of the differences between RRA and HBSE outputs for peak anterior-posterior force.

The Mixed Procedure

Model Information

Data Set	WORK.PEAK_STATS_BW_SHEET1
Dependent Variable	pFx
Covariance Structures	Variance Components, Autoregressive
Subject Effect	Trial(Person*Label)
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
Person	5	1 2 3 4 5
Trial	3	1 2 3
Cycle	4	1 2 3 4
Label	2	HBSE RRA

Dimensions

Covariance Parameters	4
Columns in X	15
Columns in Z	35
Subjects	1
Max Obs per Subject	120

Number of Observations

Number of Observations Read	120
Number of Observations Used	120
Number of Observations Not Used	0

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	-499.97427207	
1	2	-599.30486834	0.00035320
2	1	-599.46513604	0.00002003
3	1	-599.47350618	0.00000008
4	1	-599.47353756	0.00000000

Convergence criteria met.

Covariance Parameter Estimates					
Cov Parm	Subject	Estimate	Alpha	Lower	Upper
Trial(Person*Label)		0.000088	0.05	-0.00008	0.000259
Person		0.000274	0.05	-0.00015	0.000700
AR(1)	Trial(Person*Label)	0.4939	0.05	0.1419	0.8459
Residual		0.000225	0.05	0.000125	0.000520

Asymptotic Covariance Matrix of Estimates					
Row	Cov Parm	CovP1	CovP2	CovP3	CovP4
1	Trial(Person*Label)	7.649E-9	-414E-12	-0.00001	-5.14E-9
2	Person	-414E-12	4.723E-8	-3.89E-7	-155E-12
3	AR(1)	-0.00001	-3.89E-7	0.03225	0.000013
4	Residual	-5.14E-9	-155E-12	0.000013	6.305E-9

Fit Statistics	
-2 Res Log Likelihood	-599.5
AIC (Smaller is Better)	-591.5
AICC (Smaller is Better)	-591.1
BIC (Smaller is Better)	-585.9

Null Model Likelihood Ratio Test		
DF	Chi-Square	Pr > ChiSq
3	99.50	<.0001

Solution for Fixed Effects							
Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t
Intercept			-0.07741	0.008696	6.05	-8.90	0.0001
Cycle	1		0.000102	0.005395	38.6	0.02	0.9851
Cycle	2		0.001392	0.005037	65.4	0.28	0.7831
Cycle	3		0.006105	0.004112	79.2	1.48	0.1416
Cycle	4		0	.	.	.	.
Label	HBSE		0.01003	0.006459	53.2	1.55	0.1264
Label	RRA		0	.	.	.	.
Cycle*Label	HBSE 1		0.000676	0.007630	38.6	0.09	0.9299
Cycle*Label	RRA 1		0	.	.	.	.
Cycle*Label	HBSE 2		-0.00278	0.007123	65.4	-0.39	0.6973
Cycle*Label	RRA 2		0	.	.	.	.
Cycle*Label	HBSE 3		0.000559	0.005816	79.2	0.10	0.9236

Solution for Fixed Effects

Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t
Cycle*Label	RRA	3	0	.	.	.	.
Cycle*Label	HBSE	4	0	.	.	.	.
Cycle*Label	RRA	4	0	.	.	.	.

Solution for Random Effects

Effect	Label	Person	Trial	Estimate	Std Err	Pred	DF	t Value	Pr > t
Trial(Person*Label)	HBSE	1	1	0.006712	0.009938	6.34	0.68	0.5233	
Trial(Person*Label)	HBSE	1	2	0.000058	0.009938	6.34	0.01	0.9955	
Trial(Person*Label)	HBSE	1	3	-0.00117	0.009938	6.34	-0.12	0.9102	
Trial(Person*Label)	RRA	1	1	-0.00189	0.009938	6.34	-0.19	0.8550	
Trial(Person*Label)	RRA	1	2	-0.00194	0.009938	6.34	-0.20	0.8511	
Trial(Person*Label)	RRA	1	3	-0.00557	0.009938	6.34	-0.56	0.5944	
Trial(Person*Label)	HBSE	2	1	0.001439	0.009938	6.34	0.14	0.8893	
Trial(Person*Label)	HBSE	2	2	-0.00971	0.009938	6.34	-0.98	0.3642	
Trial(Person*Label)	HBSE	2	3	0.001771	0.009938	6.34	0.18	0.8641	
Trial(Person*Label)	RRA	2	1	0.009283	0.009938	6.34	0.93	0.3844	
Trial(Person*Label)	RRA	2	2	-0.00449	0.009938	6.34	-0.45	0.6661	
Trial(Person*Label)	RRA	2	3	0.003285	0.009938	6.34	0.33	0.7516	
Trial(Person*Label)	HBSE	3	1	-0.00419	0.009938	6.34	-0.42	0.6873	
Trial(Person*Label)	HBSE	3	2	0.000483	0.009938	6.34	0.05	0.9628	
Trial(Person*Label)	HBSE	3	3	-0.00043	0.009938	6.34	-0.04	0.9669	
Trial(Person*Label)	RRA	3	1	0.002722	0.009938	6.34	0.27	0.7928	
Trial(Person*Label)	RRA	3	2	0.002948	0.009938	6.34	0.30	0.7762	
Trial(Person*Label)	RRA	3	3	0.002245	0.009938	6.34	0.23	0.8284	
Trial(Person*Label)	HBSE	4	1	0.006440	0.009938	6.34	0.65	0.5397	
Trial(Person*Label)	HBSE	4	2	0.004490	0.009938	6.34	0.45	0.6664	
Trial(Person*Label)	HBSE	4	3	0.008022	0.009938	6.34	0.81	0.4487	
Trial(Person*Label)	RRA	4	1	-0.00973	0.009938	6.34	-0.98	0.3633	
Trial(Person*Label)	RRA	4	2	-0.01171	0.009938	6.34	-1.18	0.2809	
Trial(Person*Label)	RRA	4	3	-0.00409	0.009938	6.34	-0.41	0.6942	
Trial(Person*Label)	HBSE	5	1	-0.00016	0.009938	6.34	-0.02	0.9875	
Trial(Person*Label)	HBSE	5	2	-0.00626	0.009938	6.34	-0.63	0.5508	
Trial(Person*Label)	HBSE	5	3	-0.00750	0.009938	6.34	-0.75	0.4777	
Trial(Person*Label)	RRA	5	1	0.008462	0.009938	6.34	0.85	0.4255	
Trial(Person*Label)	RRA	5	2	0.006348	0.009938	6.34	0.64	0.5453	
Trial(Person*Label)	RRA	5	3	0.004140	0.009938	6.34	0.42	0.6907	

Solution for Random Effects

Effect	Label	Person	Trial	Estimate	Std Err	Pred	DF	t Value	Pr > t
Person		1		-0.01189	0.008981	5.91		-1.32	0.2346
Person		2		0.004916	0.008981	5.91		0.55	0.6041
Person		3		0.01182	0.008981	5.91		1.32	0.2367
Person		4		-0.02059	0.008981	5.91		-2.29	0.0624
Person		5		0.01573	0.008981	5.91		1.75	0.1311

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cycle	3	64	2.54	0.0639
Label	1	24.8	3.66	0.0673
Cycle*Label	3	64	0.18	0.9086

Least Squares Means

Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle		1	-0.07195	0.008074	4.51	-8.91	0.0005	0.05	-0.09341	-0.05050
Cycle		2	-0.07239	0.008074	4.51	-8.97	0.0005	0.05	-0.09385	-0.05093
Cycle		3	-0.06601	0.008074	4.51	-8.18	0.0007	0.05	-0.08746	-0.04455
Cycle		4	-0.07239	0.008074	4.51	-8.97	0.0005	0.05	-0.09385	-0.05094
Label	HBSE		-0.06586	0.008213	4.94	-8.02	0.0005	0.05	-0.08706	-0.04467
Label	RRA		-0.07551	0.008213	4.94	-9.19	0.0003	0.05	-0.09670	-0.05431

Differences of Least Squares Means

Effect	Label	Cycle	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle		1		2	0.000439	0.002908	79.2	0.15	0.8805	0.05	-0.00535	0.006226
Cycle		1		3	-0.00595	0.003562	65.4	-1.67	0.0998	0.05	-0.01306	0.001167
Cycle		1		4	0.000440	0.003815	38.6	0.12	0.9089	0.05	-0.00728	0.008159
Cycle		2		3	-0.00638	0.002908	79.2	-2.20	0.0311	0.05	-0.01217	-0.00060
Cycle		2		4	9.453E-7	0.003562	65.4	0.00	0.9998	0.05	-0.00711	0.007113
Cycle		3		4	0.006385	0.002908	79.2	2.20	0.0311	0.05	0.000597	0.01217
Label	HBSE		RRA		0.009641	0.005039	24.8	1.91	0.0673	0.05	-0.00074	0.02002

The SAS System

The Mixed Procedure

Model Information

Data Set WORK.PEAK_STATS_BW_SHEET1
Dependent Variable pFy

Model Information

Covariance Structures	Variance Components, Autoregressive
Subject Effect	Trial(Person*Label)
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
Person	5	1 2 3 4 5
Trial	3	1 2 3
Cycle	4	1 2 3 4
Label	2	HBSE RRA

Dimensions

Covariance Parameters	4
Columns in X	15
Columns in Z	35
Subjects	1
Max Obs per Subject	120

Number of Observations

Number of Observations Read	120
Number of Observations Used	120
Number of Observations Not Used	0

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	-355.95765691	
1	2	-509.88380767	0.00170964
2	1	-510.30048706	0.00027745
3	1	-510.40843320	0.00000701
4	1	-510.41098626	0.00000001

Convergence criteria met.

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Alpha	Lower	Upper
Trial(Person*Label)		0.000246	0.05	0.000031	0.000461

Covariance Parameter Estimates					
Cov Parm	Subject	Estimate	Alpha	Lower	Upper
Person		0.001641	0.05	-0.00071	0.003997
AR(1)	Trial(Person*Label)	0.1481	0.05	-0.2223	0.5185
Residual		0.000337	0.05	0.000232	0.000535

Asymptotic Covariance Matrix of Estimates					
Row	Cov Parm	CovP1	CovP2	CovP3	CovP4
1	Trial(Person*Label)	1.204E-8	-302E-12	-7.43E-6	-2.75E-9
2	Person	-302E-12	1.445E-6	-6.76E-6	-1.74E-9
3	AR(1)	-7.43E-6	-6.76E-6	0.03572	9.186E-6
4	Residual	-2.75E-9	-1.74E-9	9.186E-6	5.069E-9

Fit Statistics	
-2 Res Log Likelihood	-510.4
AIC (Smaller is Better)	-502.4
AICC (Smaller is Better)	-502.0
BIC (Smaller is Better)	-496.8

Null Model Likelihood Ratio Test		
DF	Chi-Square	Pr > ChiSq
3	154.45	<.0001

Solution for Fixed Effects						
Effect	Label	Cycle	Estimate	Standard Error	DF	t Value Pr > t
Intercept			0.8764	0.01916	4.66	45.74 <.0001
Cycle	1		0.007146	0.006753	48.6	1.06 0.2952
Cycle	2		0.008177	0.006778	63.8	1.21 0.2321
Cycle	3		0.009225	0.006287	67	1.47 0.1469
Cycle	4		0	.	.	. .
Label	HBSE		0.03986	0.008819	58.6	4.52 <.0001
Label	RRA		0	.	.	. .
Cycle*Label	HBSE 1		-0.00279	0.009550	48.6	-0.29 0.7714
Cycle*Label	RRA 1		0	.	.	. .
Cycle*Label	HBSE 2		-0.00316	0.009585	63.8	-0.33 0.7430
Cycle*Label	RRA 2		0	.	.	. .
Cycle*Label	HBSE 3		0.000377	0.008891	67	0.04 0.9663
Cycle*Label	RRA 3		0	.	.	. .
Cycle*Label	HBSE 4		0	.	.	. .

Solution for Fixed Effects

Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t
Cycle*Label	RRA	4	0	.	.	.	.

Solution for Random Effects

Effect	Label	Person	Trial	Estimate	Std Err	Pred	DF	t Value	Pr > t
Trial(Person*Label)	HBSE	1	1	0.000876	0.01092	30	0.08	0.9366	
Trial(Person*Label)	HBSE	1	2	-0.02582	0.01092	30	-2.36	0.0247	
Trial(Person*Label)	HBSE	1	3	0.02172	0.01092	30	1.99	0.0558	
Trial(Person*Label)	RRA	1	1	0.01972	0.01092	30	1.81	0.0810	
Trial(Person*Label)	RRA	1	2	-0.01735	0.01092	30	-1.59	0.1225	
Trial(Person*Label)	RRA	1	3	0.01089	0.01092	30	1.00	0.3264	
Trial(Person*Label)	HBSE	2	1	0.005287	0.01092	30	0.48	0.6317	
Trial(Person*Label)	HBSE	2	2	-0.01585	0.01092	30	-1.45	0.1569	
Trial(Person*Label)	HBSE	2	3	0.001045	0.01092	30	0.10	0.9244	
Trial(Person*Label)	RRA	2	1	0.007807	0.01092	30	0.71	0.4801	
Trial(Person*Label)	RRA	2	2	-0.01027	0.01092	30	-0.94	0.3542	
Trial(Person*Label)	RRA	2	3	0.008574	0.01092	30	0.79	0.4384	
Trial(Person*Label)	HBSE	3	1	-0.01646	0.01092	30	-1.51	0.1422	
Trial(Person*Label)	HBSE	3	2	0.006128	0.01092	30	0.56	0.5788	
Trial(Person*Label)	HBSE	3	3	-0.00536	0.01092	30	-0.49	0.6271	
Trial(Person*Label)	RRA	3	1	-0.00246	0.01092	30	-0.22	0.8236	
Trial(Person*Label)	RRA	3	2	0.01672	0.01092	30	1.53	0.1363	
Trial(Person*Label)	RRA	3	3	0.001729	0.01092	30	0.16	0.8752	
Trial(Person*Label)	HBSE	4	1	0.005432	0.01092	30	0.50	0.6225	
Trial(Person*Label)	HBSE	4	2	0.004401	0.01092	30	0.40	0.6898	
Trial(Person*Label)	HBSE	4	3	-0.00607	0.01092	30	-0.56	0.5822	
Trial(Person*Label)	RRA	4	1	0.002705	0.01092	30	0.25	0.8060	
Trial(Person*Label)	RRA	4	2	0.001819	0.01092	30	0.17	0.8688	
Trial(Person*Label)	RRA	4	3	-0.01350	0.01092	30	-1.24	0.2259	
Trial(Person*Label)	HBSE	5	1	0.02109	0.01092	30	1.93	0.0628	
Trial(Person*Label)	HBSE	5	2	-0.00039	0.01092	30	-0.04	0.9715	
Trial(Person*Label)	HBSE	5	3	0.003968	0.01092	30	0.36	0.7189	
Trial(Person*Label)	RRA	5	1	-0.00044	0.01092	30	-0.04	0.9682	
Trial(Person*Label)	RRA	5	2	-0.01386	0.01092	30	-1.27	0.2141	
Trial(Person*Label)	RRA	5	3	-0.01209	0.01092	30	-1.11	0.2771	
Person		1		0.06693	0.01935	4.77	3.46	0.0195	
Person		2		-0.02275	0.01935	4.77	-1.18	0.2950	

Solution for Random Effects

Effect	Label	Person	Trial	Estimate	Std Err	Pred	DF	t Value	Pr > t
Person		3		0.002001	0.01935	4.77	0.10	0.9219	
Person		4		-0.03476	0.01935	4.77	-1.80	0.1351	
Person		5		-0.01142	0.01935	4.77	-0.59	0.5821	

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cycle	3	57.8	1.51	0.2227
Label	1	24	32.33	<.0001
Cycle*Label	3	57.8	0.07	0.9757

Least Squares Means

Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle		1	0.9021	0.01865	4.18	48.38	<.0001	0.05	0.8512	0.9529
Cycle		2	0.9029	0.01865	4.18	48.42	<.0001	0.05	0.8520	0.9538
Cycle		3	0.9057	0.01865	4.18	48.58	<.0001	0.05	0.8548	0.9566
Cycle		4	0.8963	0.01865	4.18	48.07	<.0001	0.05	0.8454	0.9472
Label	HBSE		0.9210	0.01874	4.28	49.15	<.0001	0.05	0.8703	0.9717
Label	RRA		0.8825	0.01874	4.28	47.10	<.0001	0.05	0.8318	0.9332

Differences of Least Squares Means

Effect	Label	Cycle	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle		1		2	-0.00085	0.004445	67	-0.19	0.8493	0.05	-0.00972	0.008026
Cycle		1		3	-0.00366	0.004793	63.8	-0.76	0.4475	0.05	-0.01324	0.005912
Cycle		1		4	0.005751	0.004775	48.6	1.20	0.2343	0.05	-0.00385	0.01535
Cycle		2		3	-0.00282	0.004445	67	-0.63	0.5287	0.05	-0.01169	0.006058
Cycle		2		4	0.006599	0.004793	63.8	1.38	0.1734	0.05	-0.00298	0.01617
Cycle		3		4	0.009414	0.004445	67	2.12	0.0379	0.05	0.000541	0.01829
Label	HBSE		RRA		0.03847	0.006765	24	5.69	<.0001	0.05	0.02451	0.05243

The SAS System

The Mixed Procedure

Model Information

Data Set

WORK.PEAK_STATS_BW_SHEET1

Model Information

Dependent Variable	pFz
Covariance Structures	Variance Components, Autoregressive
Subject Effect	Trial(Person*Label)
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
Person	5	1 2 3 4 5
Trial	3	1 2 3
Cycle	4	1 2 3 4
Label	2	HBSE RRA

Dimensions

Covariance Parameters	4
Columns in X	15
Columns in Z	35
Subjects	1
Max Obs per Subject	120

Number of Observations

Number of Observations Read	120
Number of Observations Used	120
Number of Observations Not Used	0

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	-628.20076960	
1	2	-694.90758237	0.00000674
2	1	-694.91055600	0.00000001

Convergence criteria met.

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Alpha	Lower	Upper
Trial(Person*Label)		0.000014	0.05	-0.00001	0.000041
Person		0.000097	0.05	-0.00005	0.000241

Covariance Parameter Estimates					
Cov Parm	Subject	Estimate	Alpha	Lower	Upper
AR(1)	Trial(Person*Label)	0.09705	0.05	-0.2506	0.4447
Residual		0.000079	0.05	0.000055	0.000121

Asymptotic Covariance Matrix of Estimates					
Row	Cov Parm	CovP1	CovP2	CovP3	CovP4
1	Trial(Person*Label)	1.98E-10	-405E-14	-1.53E-6	-125E-12
2	Person	-405E-14	5.353E-9	-3E-7	-161E-13
3	AR(1)	-1.53E-6	-3E-7	0.03146	1.691E-6
4	Residual	-125E-12	-161E-13	1.691E-6	2.39E-10

Fit Statistics	
-2 Res Log Likelihood	-694.9
AIC (Smaller is Better)	-686.9
AICC (Smaller is Better)	-686.5
BIC (Smaller is Better)	-681.3

Null Model Likelihood Ratio Test		
DF	Chi-Square	Pr > ChiSq
3	66.71	<.0001

Solution for Fixed Effects							
Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t
Intercept			0.03220	0.005064	6.13	6.36	0.0007
Cycle	1		-0.00076	0.003255	53.6	-0.23	0.8171
Cycle	2		0.004137	0.003282	64	1.26	0.2121
Cycle	3		0.001288	0.003115	67.8	0.41	0.6805
Cycle	4		0	.	.	.	.
Label	HBSE		0.01159	0.003515	91.7	3.30	0.0014
Label	RRA		0	.	.	.	.
Cycle*Label	HBSE 1		0.003889	0.004603	53.6	0.84	0.4019
Cycle*Label	RRA 1		0	.	.	.	.
Cycle*Label	HBSE 2		-0.00381	0.004642	64	-0.82	0.4150
Cycle*Label	RRA 2		0	.	.	.	.
Cycle*Label	HBSE 3		-0.00090	0.004406	67.8	-0.20	0.8393
Cycle*Label	RRA 3		0	.	.	.	.
Cycle*Label	HBSE 4		0	.	.	.	.
Cycle*Label	RRA 4		0	.	.	.	.

Solution for Random Effects

Effect	Label	Person	Trial	Estimate	Std Err	Pred	DF	t Value	Pr > t
Trial(Person*Label)	HBSE 1	1	1	0.002410	0.003907	4.53	0.62	0.5670	
Trial(Person*Label)	HBSE 1	2	2	0.001861	0.003907	4.53	0.48	0.6559	
Trial(Person*Label)	HBSE 1	3	3	0.001222	0.003907	4.53	0.31	0.7683	
Trial(Person*Label)	RRA 1	1	1	-0.00406	0.003907	4.53	-1.04	0.3507	
Trial(Person*Label)	RRA 1	2	2	0.000216	0.003907	4.53	0.06	0.9583	
Trial(Person*Label)	RRA 1	3	3	0.000154	0.003907	4.53	0.04	0.9703	
Trial(Person*Label)	HBSE 2	1	1	0.000339	0.003907	4.53	0.09	0.9345	
Trial(Person*Label)	HBSE 2	2	2	-0.00138	0.003907	4.53	-0.35	0.7390	
Trial(Person*Label)	HBSE 2	3	3	0.001706	0.003907	4.53	0.44	0.6824	
Trial(Person*Label)	RRA 2	1	1	-0.00123	0.003907	4.53	-0.31	0.7673	
Trial(Person*Label)	RRA 2	2	2	-0.00051	0.003907	4.53	-0.13	0.9011	
Trial(Person*Label)	RRA 2	3	3	0.001071	0.003907	4.53	0.27	0.7960	
Trial(Person*Label)	HBSE 3	1	1	-0.00064	0.003907	4.53	-0.16	0.8772	
Trial(Person*Label)	HBSE 3	2	2	0.003863	0.003907	4.53	0.99	0.3727	
Trial(Person*Label)	HBSE 3	3	3	-0.00271	0.003907	4.53	-0.69	0.5217	
Trial(Person*Label)	RRA 3	1	1	-0.00477	0.003907	4.53	-1.22	0.2817	
Trial(Person*Label)	RRA 3	2	2	0.003622	0.003907	4.53	0.93	0.4006	
Trial(Person*Label)	RRA 3	3	3	0.000663	0.003907	4.53	0.17	0.8725	
Trial(Person*Label)	HBSE 4	1	1	0.001832	0.003907	4.53	0.47	0.6609	
Trial(Person*Label)	HBSE 4	2	2	-0.00087	0.003907	4.53	-0.22	0.8334	
Trial(Person*Label)	HBSE 4	3	3	-0.00294	0.003907	4.53	-0.75	0.4884	
Trial(Person*Label)	RRA 4	1	1	0.002038	0.003907	4.53	0.52	0.6264	
Trial(Person*Label)	RRA 4	2	2	-0.00003	0.003907	4.53	-0.01	0.9949	
Trial(Person*Label)	RRA 4	3	3	0.000197	0.003907	4.53	0.05	0.9619	
Trial(Person*Label)	HBSE 5	1	1	-0.00002	0.003907	4.53	-0.01	0.9956	
Trial(Person*Label)	HBSE 5	2	2	-0.00141	0.003907	4.53	-0.36	0.7338	
Trial(Person*Label)	HBSE 5	3	3	-0.00325	0.003907	4.53	-0.83	0.4473	
Trial(Person*Label)	RRA 5	1	1	0.000069	0.003907	4.53	0.02	0.9867	
Trial(Person*Label)	RRA 5	2	2	0.000589	0.003907	4.53	0.15	0.8866	
Trial(Person*Label)	RRA 5	3	3	0.001982	0.003907	4.53	0.51	0.6357	
Person		1		0.01261	0.004927	5.24	2.56	0.0485	
Person		2		-0.00006	0.004927	5.24	-0.01	0.9907	
Person		3		0.000187	0.004927	5.24	0.04	0.9712	
Person		4		0.001583	0.004927	5.24	0.32	0.7604	
Person		5		-0.01432	0.004927	5.24	-2.91	0.0317	

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cycle	3	59.2	0.31	0.8169
Label	1	24.1	27.61	<.0001
Cycle*Label	3	59.2	1.01	0.3952

Least Squares Means

Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle		1	0.03919	0.004749	4.75	8.25	0.0005	0.05	0.02679	0.05159
Cycle		2	0.04023	0.004749	4.75	8.47	0.0005	0.05	0.02783	0.05263
Cycle		3	0.03884	0.004749	4.75	8.18	0.0006	0.05	0.02644	0.05124
Cycle		4	0.03800	0.004749	4.75	8.00	0.0006	0.05	0.02560	0.05040
Label	HBSE		0.04476	0.004671	4.48	9.58	0.0004	0.05	0.03232	0.05719
Label	RRA		0.03337	0.004671	4.48	7.14	0.0013	0.05	0.02094	0.04581

Differences of Least Squares Means

Effect	Label	Cycle	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle		1		2	-0.00104	0.002203	67.8	-0.47	0.6368	0.05	-0.00544	0.003351
Cycle		1		3	0.000348	0.002321	64	0.15	0.8812	0.05	-0.00429	0.004985
Cycle		1		4	0.001188	0.002301	53.6	0.52	0.6078	0.05	-0.00343	0.005803
Cycle		2		3	0.001393	0.002203	67.8	0.63	0.5293	0.05	-0.00300	0.005789
Cycle		2		4	0.002233	0.002321	64	0.96	0.3396	0.05	-0.00240	0.006870
Cycle		3		4	0.000840	0.002203	67.8	0.38	0.7042	0.05	-0.00356	0.005236
Label	HBSE		RRA		0.01139	0.002167	24.1	5.25	<.0001	0.05	0.006915	0.01586

The SAS System

The Mixed Procedure

Model Information

Data Set	WORK.PEAK_STATS_BW_SHEET1
Dependent Variable	pMx
Covariance Structures	Variance Components, Autoregressive
Subject Effect	Trial(Person*Label)
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
Person	5	1 2 3 4 5
Trial	3	1 2 3
Cycle	4	1 2 3 4
Label	2	HBSE RRA

Dimensions

Covariance Parameters	4
Columns in X	15
Columns in Z	35
Subjects	1
Max Obs per Subject	120

Number of Observations

Number of Observations Read	120
Number of Observations Used	120
Number of Observations Not Used	0

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	-881.64993503	
1	2	-974.65327310	0.00300673
2	3	-975.47932345	0.00023861
3	1	-975.59961710	0.00001799
4	1	-975.61046556	0.00000006
5	1	-975.61049863	0.00000000

Convergence criteria met.

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Alpha	Lower	Upper
Trial(Person*Label)		8.454E-6	0.05	-6.72E-6	0.000024
Person		-5.84E-8	0.05	-4E-6	3.884E-6
AR(1)	Trial(Person*Label)	0.7187	0.05	0.3499	1.0874
Residual		0.000011	0.05	4.353E-6	0.000074

Asymptotic Covariance Matrix of Estimates

Row	Cov Parm	CovP1	CovP2	CovP3	CovP4
1	Trial(Person*Label)	6E-11	-321E-14	-1.14E-6	-458E-13
2	Person	-321E-14	4.05E-12	-1.21E-8	

Asymptotic Covariance Matrix of Estimates

Row	Cov Parm	CovP1	CovP2	CovP3	CovP4
3	AR(1)	-1.14E-6	-1.21E-8	0.03539	1.353E-6
4	Residual	-458E-13		1.353E-6	5.48E-11

Fit Statistics

-2 Res Log Likelihood -975.6

AIC (Smaller is Better) -967.6

AICC (Smaller is Better) -967.2

BIC (Smaller is Better) -962.0

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
3	93.96	<.0001

Solution for Fixed Effects

Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t
Intercept			-0.00456	0.001145	20.6	-3.98	0.0007
Cycle	1		0.000088	0.001162	38.5	0.08	0.9403
Cycle	2		0.000049	0.001023	69	0.05	0.9622
Cycle	3		0.000043	0.000780	79.3	0.05	0.9563
Cycle	4		0	.	.	.	.
Label	HBSE		-0.02537	0.001627	34	-15.60	<.0001
Label	RRA		0	.	.	.	.
Cycle*Label	HBSE 1		-0.00105	0.001643	38.5	-0.64	0.5256
Cycle*Label	RRA 1		0	.	.	.	.
Cycle*Label	HBSE 2		-0.00041	0.001447	69	-0.28	0.7794
Cycle*Label	RRA 2		0	.	.	.	.
Cycle*Label	HBSE 3		-0.00141	0.001102	79.3	-1.27	0.2061
Cycle*Label	RRA 3		0	.	.	.	.
Cycle*Label	HBSE 4		0	.	.	.	.
Cycle*Label	RRA 4		0	.	.	.	.

Solution for Random Effects

Effect	Label	Person	Trial	Estimate	Std Err	Pred	DF	t Value	Pr > t
Trial(Person*Label)	HBSE 1	1	1	0.002669	0.002066	112	1.29	0.1989	
Trial(Person*Label)	HBSE 1	2	2	-0.00200	0.002066	112	-0.97	0.3353	
Trial(Person*Label)	HBSE 1	3	3	-0.00171	0.002066	112	-0.83	0.4089	
Trial(Person*Label)	RRA 1	1	1	0.000518	0.002066	112	0.25	0.8025	

Solution for Random Effects

Effect	Label	Person	Trial	Estimate	Std Err	Pred	DF	t Value	Pr > t
Trial(Person*Label)	RRA	1	2	-0.00244	0.002066	112		-1.18	0.2408
Trial(Person*Label)	RRA	1	3	-0.00064	0.002066	112		-0.31	0.7567
Trial(Person*Label)	HBSE	2	1	0.005273	0.002066	112		2.55	0.0120
Trial(Person*Label)	HBSE	2	2	0.002003	0.002066	112		0.97	0.3342
Trial(Person*Label)	HBSE	2	3	0.004222	0.002066	112		2.04	0.0433
Trial(Person*Label)	RRA	2	1	-0.00060	0.002066	112		-0.29	0.7719
Trial(Person*Label)	RRA	2	2	-0.00290	0.002066	112		-1.41	0.1626
Trial(Person*Label)	RRA	2	3	-0.00066	0.002066	112		-0.32	0.7500
Trial(Person*Label)	HBSE	3	1	-0.00021	0.002066	112		-0.10	0.9174
Trial(Person*Label)	HBSE	3	2	0.000267	0.002066	112		0.13	0.8974
Trial(Person*Label)	HBSE	3	3	-0.00061	0.002066	112		-0.29	0.7696
Trial(Person*Label)	RRA	3	1	0.001501	0.002066	112		0.73	0.4689
Trial(Person*Label)	RRA	3	2	-0.00013	0.002066	112		-0.07	0.9481
Trial(Person*Label)	RRA	3	3	0.001104	0.002066	112		0.53	0.5942
Trial(Person*Label)	HBSE	4	1	-0.00092	0.002066	112		-0.45	0.6564
Trial(Person*Label)	HBSE	4	2	0.000450	0.002066	112		0.22	0.8278
Trial(Person*Label)	HBSE	4	3	-0.00391	0.002066	112		-1.89	0.0608
Trial(Person*Label)	RRA	4	1	-0.00021	0.002066	112		-0.10	0.9196
Trial(Person*Label)	RRA	4	2	-0.00037	0.002066	112		-0.18	0.8576
Trial(Person*Label)	RRA	4	3	-0.00122	0.002066	112		-0.59	0.5563
Trial(Person*Label)	HBSE	5	1	-0.00225	0.002066	112		-1.09	0.2773
Trial(Person*Label)	HBSE	5	2	-0.00172	0.002066	112		-0.83	0.4066
Trial(Person*Label)	HBSE	5	3	-0.00154	0.002066	112		-0.75	0.4564
Trial(Person*Label)	RRA	5	1	0.002547	0.002066	112		1.23	0.2201
Trial(Person*Label)	RRA	5	2	0.002020	0.002066	112		0.98	0.3301
Trial(Person*Label)	RRA	5	3	0.001485	0.002066	112		0.72	0.4737
Person		1		0.000025		0	112	Infty	<.0001
Person		2		-0.00005		0	112	-Infty	<.0001
Person		3		-0.00001		0	112	-Infty	<.0001
Person		4		0.000043		0	112	Infty	<.0001
Person		5		-3.68E-6		0	112	-Infty	<.0001

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cycle	3	63.6	0.76	0.5211
Label	1	23.9	342.37	<.0001
Cycle*Label	3	63.6	0.84	0.4746

Least Squares Means

Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle		1	-0.01768	0.000806	6.09	-21.93	<.0001	0.05	-0.01964	-0.01571
Cycle		2	-0.01739	0.000806	6.09	-21.58	<.0001	0.05	-0.01936	-0.01543
Cycle		3	-0.01790	0.000806	6.09	-22.20	<.0001	0.05	-0.01986	-0.01593
Cycle		4	-0.01724	0.000806	6.09	-21.39	<.0001	0.05	-0.01921	-0.01527
Label	HBSE		-0.03060	0.000991	14.2	-30.87	<.0001	0.05	-0.03272	-0.02847
Label	RRA		-0.00451	0.000991	14.2	-4.55	0.0004	0.05	-0.00663	-0.00239

Differences of Least Squares Means

Effect	Label	Cycle	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle		1		2	-0.00028	0.000551	79.3	-0.52	0.6080	0.05	-0.00138	0.000813
Cycle		1		3	0.000221	0.000724	69	0.31	0.7608	0.05	-0.00122	0.001665
Cycle		1		4	-0.00044	0.000822	38.5	-0.53	0.5965	0.05	-0.00210	0.001224
Cycle		2		3	0.000505	0.000551	79.3	0.92	0.3623	0.05	-0.00059	0.001602
Cycle		2		4	-0.00015	0.000724	69	-0.21	0.8313	0.05	-0.00160	0.001289
Cycle		3		4	-0.00066	0.000551	79.3	-1.20	0.2348	0.05	-0.00176	0.000437
Label	HBSE		RRA		-0.02609	0.001410	23.9	-18.50	<.0001	0.05	-0.02900	-0.02318

The SAS System

The Mixed Procedure

Model Information

Data Set	WORK.PEAK_STATS_BW_SHEET1
Dependent Variable	pMy
Covariance Structures	Variance Components, Autoregressive
Subject Effect	Trial(Person*Label)
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
Person	5	1 2 3 4 5
Trial	3	1 2 3
Cycle	4	1 2 3 4

Class Level Information

Class	Levels	Values
Label	2	HBSE RRA

Dimensions

Covariance Parameters	4
Columns in X	15
Columns in Z	35
Subjects	1
Max Obs per Subject	120

Number of Observations

Number of Observations Read	120
Number of Observations Used	120
Number of Observations Not Used	0

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	-900.54655035	
1	2	-1103.18087174	0.00413340
2	1	-1104.75558852	0.00132030
3	1	-1105.72828974	0.00012640
4	1	-1105.81787748	0.00000257
5	1	-1105.81958731	0.00000000

Convergence criteria met.

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Alpha	Lower	Upper
Trial(Person*Label)		1.313E-6	.	.	.
Person		0.000015	0.05	-6.17E-6	0.000036
AR(1)	Trial(Person*Label)	-0.1761	0.05	-0.4377	0.08546
Residual		1.412E-6	.	.	.

Asymptotic Covariance Matrix of Estimates

Row	Cov Parm	CovP1	CovP2	CovP3	CovP4
1	Trial(Person*Label)			-9.43E-9	
2	Person		1.17E-10	-7.74E-9	
3	AR(1)	-9.43E-9	-7.74E-9	0.01781	5.049E-9
4	Residual			5.049E-9	

Fit Statistics

-2 Res Log Likelihood -1105.8

AIC (Smaller is Better) -1097.8

AICC (Smaller is Better) -1097.4

BIC (Smaller is Better) -1092.2

Null Model Likelihood Ratio Test

DF Chi-Square Pr > ChiSq

3 205.27 <.0001

Solution for Fixed Effects

Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t
Intercept			-0.00642	0.001786	4.34	-3.60	0.0198
Cycle	1		0.000045	0.000433	83.3	0.10	0.9166
Cycle	2		0.000422	0.000431	67.8	0.98	0.3307
Cycle	3		-0.00002	0.000471	63.8	-0.04	0.9716
Cycle	4		0	.	.	.	.
Label	HBSE		0.000064	0.000603	61.8	0.11	0.9160
Label	RRA		0	.	.	.	.
Cycle*Label	HBSE 1		-0.00020	0.000613	83.3	-0.33	0.7415
Cycle*Label	RRA 1		0	.	.	.	.
Cycle*Label	HBSE 2		-0.00072	0.000609	67.8	-1.18	0.2414
Cycle*Label	RRA 2		0	.	.	.	.
Cycle*Label	HBSE 3		0.000023	0.000667	63.8	0.03	0.9724
Cycle*Label	RRA 3		0	.	.	.	.
Cycle*Label	HBSE 4		0	.	.	.	.
Cycle*Label	RRA 4		0	.	.	.	.

Solution for Random Effects

Effect	Label	Person	Trial	Estimate	Std Err	Pred DF	t Value	Pr > t
Trial(Person*Label)	HBSE 1	1		0.001382	0.000672	36	2.06	0.0469
Trial(Person*Label)	HBSE 1	2		-0.00030	0.000672	36	-0.44	0.6624
Trial(Person*Label)	HBSE 1	3		0.000639	0.000672	36	0.95	0.3477
Trial(Person*Label)	RRA 1	1		0.000832	0.000672	36	1.24	0.2235
Trial(Person*Label)	RRA 1	2		-0.00243	0.000672	36	-3.62	0.0009
Trial(Person*Label)	RRA 1	3		-0.00070	0.000672	36	-1.05	0.3017
Trial(Person*Label)	HBSE 2	1		0.001215	0.000672	36	1.81	0.0787
Trial(Person*Label)	HBSE 2	2		0.000805	0.000672	36	1.20	0.2385
Trial(Person*Label)	HBSE 2	3		0.000564	0.000672	36	0.84	0.4063

Solution for Random Effects

Effect	Label	Person	Trial	Estimate	Std Err	Pred DF	t Value	Pr > t
Trial(Person*Label)	RRA	2	1	-0.00006	0.000672	36	-0.09	0.9317
Trial(Person*Label)	RRA	2	2	-0.00159	0.000672	36	-2.37	0.0233
Trial(Person*Label)	RRA	2	3	-0.00078	0.000672	36	-1.16	0.2557
Trial(Person*Label)	HBSE	3	1	-0.00009	0.000672	36	-0.13	0.8978
Trial(Person*Label)	HBSE	3	2	0.000443	0.000672	36	0.66	0.5138
Trial(Person*Label)	HBSE	3	3	-0.00004	0.000672	36	-0.05	0.9582
Trial(Person*Label)	RRA	3	1	0.000340	0.000672	36	0.51	0.6163
Trial(Person*Label)	RRA	3	2	-0.00039	0.000672	36	-0.57	0.5696
Trial(Person*Label)	RRA	3	3	-0.00010	0.000672	36	-0.15	0.8785
Trial(Person*Label)	HBSE	4	1	-0.00084	0.000672	36	-1.25	0.2192
Trial(Person*Label)	HBSE	4	2	0.000065	0.000672	36	0.10	0.9238
Trial(Person*Label)	HBSE	4	3	-0.00090	0.000672	36	-1.34	0.1899
Trial(Person*Label)	RRA	4	1	0.000715	0.000672	36	1.06	0.2942
Trial(Person*Label)	RRA	4	2	0.000059	0.000672	36	0.09	0.9304
Trial(Person*Label)	RRA	4	3	0.000898	0.000672	36	1.34	0.1898
Trial(Person*Label)	HBSE	5	1	-0.00086	0.000672	36	-1.28	0.2098
Trial(Person*Label)	HBSE	5	2	-0.00033	0.000672	36	-0.49	0.6244
Trial(Person*Label)	HBSE	5	3	-0.00177	0.000672	36	-2.63	0.0124
Trial(Person*Label)	RRA	5	1	0.001609	0.000672	36	2.40	0.0219
Trial(Person*Label)	RRA	5	2	0.000681	0.000672	36	1.01	0.3176
Trial(Person*Label)	RRA	5	3	0.000916	0.000672	36	1.36	0.1809
Person		1		-0.00662	0.001794	4.4	-3.69	0.0177
Person		2		0.001826	0.001794	4.4	1.02	0.3615
Person		3		0.001962	0.001794	4.4	1.09	0.3304
Person		4		-8.96E-6	0.001794	4.4	-0.00	0.9962
Person		5		0.002843	0.001794	4.4	1.58	0.1817

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cycle	3	62.9	0.04	0.9887
Label	1	24.1	0.12	0.7284
Cycle*Label	3	62.9	0.60	0.6144

Least Squares Means

Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle		1	-0.00645	0.001760	4.1	-3.66	0.0206	0.05	-0.01129	-0.00161
Cycle		2	-0.00633	0.001760	4.1	-3.60	0.0219	0.05	-0.01117	-0.00149

Least Squares Means

Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle		3	-0.00640	0.001760	4.1	-3.63	0.0212	0.05	-0.01124	-0.00156
Cycle		4	-0.00639	0.001760	4.1	-3.63	0.0212	0.05	-0.01123	-0.00155
Label	HBSE		-0.00647	0.001764	4.14	-3.67	0.0202	0.05	-0.01130	-0.00164
Label	RRA		-0.00631	0.001764	4.14	-3.58	0.0219	0.05	-0.01114	-0.00148

Differences of Least Squares Means

Effect	Label	Cycle	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle		1		2	-0.00012	0.000333	63.8	-0.35	0.7246	0.05	-0.00078	0.000548
Cycle		1		3	-0.00005	0.000305	67.8	-0.17	0.8685	0.05	-0.00066	0.000557
Cycle		1		4	-0.00006	0.000306	83.3	-0.18	0.8557	0.05	-0.00067	0.000553
Cycle		2		3	0.000067	0.000333	63.8	0.20	0.8406	0.05	-0.00060	0.000733
Cycle		2		4	0.000062	0.000305	67.8	0.20	0.8391	0.05	-0.00055	0.000670
Cycle		3		4	-5.25E-6	0.000333	63.8	-0.02	0.9875	0.05	-0.00067	0.000661
Label	HBSE		RRA		-0.00016	0.000459	24.1	-0.35	0.7284	0.05	-0.00111	0.000785

The SAS System

The Mixed Procedure

Model Information

Data Set	WORK.PEAK_STATS_BW_SHEET1
Dependent Variable	pMz
Covariance Structures	Variance Components, Autoregressive
Subject Effect	Trial(Person*Label)
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
Person	5	1 2 3 4 5
Trial	3	1 2 3
Cycle	4	1 2 3 4
Label	2	HBSE RRA

Dimensions

Covariance Parameters	4
Columns in X	15
Columns in Z	35
Subjects	1
Max Obs per Subject	120

Number of Observations

Number of Observations Read	120
Number of Observations Used	120
Number of Observations Not Used	0

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	-566.87618889	
1	2	-829.40646731	0.00000013
2	1	-829.40653228	0.00000000

Convergence criteria met.

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Alpha	Lower	Upper
Trial(Person*Label)		0.000096	0.05	0.000040	0.000153
Person		0.000230	0.05	-0.00011	0.000573
AR(1)	Trial(Person*Label)	0.1537	0.05	-0.1460	0.4533
Residual		0.000012	0.05	8.411E-6	0.000018

Asymptotic Covariance Matrix of Estimates

Row	Cov Parm	CovP1	CovP2	CovP3	CovP4
1	Trial(Person*Label)	8.36E-10	-139E-12	-1.18E-7	-215E-14
2	Person	-139E-12	3.056E-8	-6.17E-8	
3	AR(1)	-1.18E-7	-6.17E-8	0.02337	2.16E-7
4	Residual	-215E-14		2.16E-7	5.37E-12

Fit Statistics

-2 Res Log Likelihood	-829.4
AIC (Smaller is Better)	-821.4
AICC (Smaller is Better)	-821.0
BIC (Smaller is Better)	-815.8

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
3	262.53	<.0001

Solution for Fixed Effects

Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t
Intercept			0.02506	0.007301	4.65	3.43	0.0209
Cycle	1		0.000971	0.001265	56.5	0.77	0.4463
Cycle	2		0.000821	0.001263	69.5	0.65	0.5180
Cycle	3		0.000950	0.001172	72.3	0.81	0.4204
Cycle	4		0	.	.	.	.
Label	HBSE		0.01616	0.003800	28	4.25	0.0002
Label	RRA		0	.	.	.	.
Cycle*Label	HBSE 1		0.000369	0.001790	56.5	0.21	0.8373
Cycle*Label	RRA 1		0	.	.	.	.
Cycle*Label	HBSE 2		0.001241	0.001787	69.5	0.69	0.4898
Cycle*Label	RRA 2		0	.	.	.	.
Cycle*Label	HBSE 3		0.001235	0.001657	72.3	0.75	0.4585
Cycle*Label	RRA 3		0	.	.	.	.
Cycle*Label	HBSE 4		0	.	.	.	.
Cycle*Label	RRA 4		0	.	.	.	.

Solution for Random Effects

Effect	Label	Person	Trial	Estimate	Std Err	Pred	DF	t Value	Pr > t
Trial(Person*Label)	HBSE 1	1		0.001715	0.004716		31	0.36	0.7186
Trial(Person*Label)	HBSE 1	2		-0.00706	0.004716		31	-1.50	0.1443
Trial(Person*Label)	HBSE 1	3		0.002210	0.004716		31	0.47	0.6427
Trial(Person*Label)	RRA 1	1		-0.00006	0.004716		31	-0.01	0.9900
Trial(Person*Label)	RRA 1	2		-0.00081	0.004716		31	-0.17	0.8651
Trial(Person*Label)	RRA 1	3		0.006465	0.004716		31	1.37	0.1803
Trial(Person*Label)	HBSE 2	1		0.003882	0.004716		31	0.82	0.4167
Trial(Person*Label)	HBSE 2	2		-0.00365	0.004716		31	-0.77	0.4446
Trial(Person*Label)	HBSE 2	3		0.003883	0.004716		31	0.82	0.4166
Trial(Person*Label)	RRA 2	1		-0.00270	0.004716		31	-0.57	0.5716
Trial(Person*Label)	RRA 2	2		-0.00541	0.004716		31	-1.15	0.2602
Trial(Person*Label)	RRA 2	3		-0.00218	0.004716		31	-0.46	0.6469
Trial(Person*Label)	HBSE 3	1		-0.00937	0.004716		31	-1.99	0.0558
Trial(Person*Label)	HBSE 3	2		-0.00904	0.004716		31	-1.92	0.0646
Trial(Person*Label)	HBSE 3	3		-0.01321	0.004716		31	-2.80	0.0087
Trial(Person*Label)	RRA 3	1		0.009453	0.004716		31	2.00	0.0538

Solution for Random Effects

Effect	Label	Person	Trial	Estimate	Std Err	Pred	DF	t Value	Pr > t
Trial(Person*Label)	RRA	3	2	0.01199	0.004716		31	2.54	0.0162
Trial(Person*Label)	RRA	3	3	0.009709	0.004716		31	2.06	0.0480
Trial(Person*Label)	HBSE	4	1	-0.00816	0.004716		31	-1.73	0.0934
Trial(Person*Label)	HBSE	4	2	-0.00685	0.004716		31	-1.45	0.1564
Trial(Person*Label)	HBSE	4	3	-0.00126	0.004716		31	-0.27	0.7914
Trial(Person*Label)	RRA	4	1	0.003995	0.004716		31	0.85	0.4034
Trial(Person*Label)	RRA	4	2	0.000569	0.004716		31	0.12	0.9047
Trial(Person*Label)	RRA	4	3	0.006817	0.004716		31	1.45	0.1583
Trial(Person*Label)	HBSE	5	1	0.01612	0.004716		31	3.42	0.0018
Trial(Person*Label)	HBSE	5	2	0.01423	0.004716		31	3.02	0.0050
Trial(Person*Label)	HBSE	5	3	0.01656	0.004716		31	3.51	0.0014
Trial(Person*Label)	RRA	5	1	-0.01382	0.004716		31	-2.93	0.0063
Trial(Person*Label)	RRA	5	2	-0.01309	0.004716		31	-2.78	0.0093
Trial(Person*Label)	RRA	5	3	-0.01094	0.004716		31	-2.32	0.0271
Person		1		0.005877	0.007718		5.39	0.76	0.4784
Person		2		-0.01476	0.007718		5.39	-1.91	0.1100
Person		3		-0.00110	0.007718		5.39	-0.14	0.8919
Person		4		-0.01169	0.007718		5.39	-1.51	0.1862
Person		5		0.02167	0.007718		5.39	2.81	0.0347

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cycle	3	64.9	1.36	0.2643
Label	1	24	21.36	0.0001
Cycle*Label	3	64.9	0.26	0.8530

Least Squares Means

Effect	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle		1	0.03429	0.007050	4.04	4.86	0.0080	0.05	0.01481	0.05378
Cycle		2	0.03458	0.007050	4.04	4.91	0.0078	0.05	0.01509	0.05407
Cycle		3	0.03471	0.007050	4.04	4.92	0.0077	0.05	0.01522	0.05419
Cycle		4	0.03314	0.007050	4.04	4.70	0.0091	0.05	0.01365	0.05263
Label	HBSE		0.04262	0.007263	4.56	5.87	0.0028	0.05	0.02338	0.06185
Label	RRA		0.02574	0.007263	4.56	3.54	0.0193	0.05	0.006511	0.04497

Differences of Least Squares Means

Effect	Label	Cycle	Label	Cycle	Estimate	Standard Error	DF	t Value	Pr > t	Alpha	Lower	Upper
Cycle	1		2		-0.00029	0.000828	72.3	-0.35	0.7308	0.05	-0.00194	0.001365
Cycle	1		3		-0.00041	0.000893	69.5	-0.46	0.6462	0.05	-0.00219	0.001370
Cycle	1		4		0.001155	0.000895	56.5	1.29	0.2020	0.05	-0.00064	0.002947
Cycle	2		3		-0.00013	0.000828	72.3	-0.15	0.8798	0.05	-0.00178	0.001526
Cycle	2		4		0.001441	0.000893	69.5	1.61	0.1112	0.05	-0.00034	0.003223
Cycle	3		4		0.001567	0.000828	72.3	1.89	0.0626	0.05	-0.00008	0.003218
Label	HBSE		RRA		0.01687	0.003651	24	4.62	0.0001	0.05	0.009339	0.02441

Appendix H. Plots of Raw Pedal, Seat, and Handlebar Data for all Participants

Provided in this appendix are plots showing raw data from the right pedal, seat, and handlebar force transducers normalized by participant body weight (forces) and body weight times height (moments). Results were generated by five cyclists cycling at 70 RPM and a moderate resistance. Two plots are provided for each force and moment direction per transducer. The first plot shows a five cycle average for each trial and the second plot shows an average of those trials per participant. This is done to give the reader an idea of how the data vary between trials. Note that the results have both variation between participants and slight offsets between participant trials. Differences between participants are expected as bicycle ergonomics and individual body types have a large effect on the resulting kinetics. Offsets in participant data trial to trial are due in part to slight transducer drift but are primarily due to differences in seating position between trials. Axes are defined as positive right, forward, and up with respect to the transducer. Note that the orientation of the pedal transducer changes with respect to the rider as the pedal moves through a complete cycle. Both the seat and handlebar transducers do not change in position or orientation.

Figure H.1: Normalized pedal anterior-posterior force averaged across five cycles for each trial.

Figure H.2: Normalized pedal anterior-posterior force averaged across five cycles and three trials for each participant.

Figure H.3: Normalized pedal medial-lateral force averaged across five cycles for each trial.

Figure H.4: Normalized pedal medial-lateral force averaged across five cycles and three trials for each participant.

Figure H.5: Normalized pedal superior-inferior force averaged across five cycles for each trial.

Figure H.6: Normalized pedal superior-inferior force averaged across five cycles and three trials for each participant.

Figure H.7: Normalized pedal anterior-posterior moment averaged across five cycles for each trial.

Figure H.8: Normalized pedal anterior-posterior moment averaged across five cycles and three trials for each participant.

Figure H.9: Normalized pedal medial-lateral moment averaged across five cycles for each trial.

Figure H.10: Normalized pedal medial-lateral moment averaged across five cycles and three trials for each participant.

Figure H.11: Normalized pedal superior-inferior moment averaged across five cycles for each trial.

Figure H.12: Normalized pedal superior-inferior moment averaged across five cycles and three trials for each participant.

Figure H.13: Normalized seat anterior-posterior force averaged across five cycles for each trial.

Figure H.14: Normalized seat anterior-posterior force averaged across five cycles and three trials for each participant.

Figure H.15: Normalized seat medial-lateral force averaged across five cycles for each trial.

Figure H.16: Normalized seat medial-lateral force averaged across five cycles and three trials for each participant.

Figure H.17: Normalized seat superior-inferior force averaged across five cycles for each trial.

Figure H.18: Normalized seat superior-inferior force averaged across five cycles and three trials for each participant.

Figure H.19: Normalized seat anterior-posterior moment averaged across five cycles for each trial.

Figure H.20: Normalized seat anterior-posterior moment averaged across five cycles and three trials for each participant.

Figure H.21: Normalized seat medial-lateral moment averaged across five cycles for each trial.

Figure H.22: Normalized seat medial-lateral moment averaged across five cycles and three trials for each participant.

Figure H.23: Normalized seat superior-inferior moment averaged across five cycles for each trial.

Figure H.24: Normalized seat superior-inferior moment averaged across five cycles and three trials for each participant.

Figure H.25: Normalized handlebar anterior-posterior force averaged across five cycles for each trial.

Figure H.26: Normalized handlebar anterior-posterior force averaged across five cycles and three trials for each participant.

Figure H.27: Normalized handlebar medial-lateral force averaged across five cycles for each trial.

Figure H.28: Normalized handlebar medial-lateral force averaged across five cycles and three trials for each participant.

Figure H.29: Normalized handlebar superior-inferior force averaged across five cycles for each trial.

Figure H.30: Normalized handlebar superior-inferior force averaged across five cycles and three trials for each participant.

Figure H.31: Normalized handlebar anterior-posterior moment averaged across five cycles for each trial.

Figure H.32: Normalized handlebar anterior-posterior moment averaged across five cycles and three trials for each participant.

Figure H.33: Normalized handlebar medial-lateral moment averaged across five cycles for each trial.

Figure H.34: Normalized handlebar medial-lateral moment averaged across five cycles and three trials for each participant.

Figure H.35: Normalized handlebar superior-inferior moment averaged across five cycles for each trial.

Figure H.36: Normalized handlebar superior-inferior moment averaged across five cycles and three trials for each participant.

Appendix I. Plots of Select Seat and Handlebar Loads versus Literature

This appendix contains plots comparing one cycle of seat and handlebar loads captured in this study to published literature. One cycle is defined by one full rotation of the right pedal starting from top center. All plots are normalized by rider weight for forces and by rider weight*height for moments. Load directions were chosen based on available published data but are representative of the most important force and moment directions to consider when analyzing cycling. All plots contain data reproduced digitally from plots found in their respective published work.

Note that both studies used for comparison in this appendix utilized an instrumented road type bicycle to collect data. This is in contrast to the instrumented stationary exercise bicycle used in this study. Additionally, both studies focused on elite cyclists riding at higher power levels than this study. These two factors are the prime contributors to the differences seen between the data from this study and published literature. However, clear similarities in general trends can be observed.

Figure I.1: Comparison of handlebar superior-inferior force data to literature.

Figure I.2: Comparison of handlebar anterior-posterior force data to literature.

Figure I.3: Comparison of seat anterior-posterior force data to literature.

Figure I.4: Comparison of seat medial-lateral force data to literature.

Figure I.5: Comparison of seat superior-inferior force data to literature.

Figure I.6: Comparison of seat anterior-posterior moment data to literature.

Appendix J. Plots of RRA versus Handlebar Seat Equivalent

Included in this appendix are plots comparing the OpenSim RRA pelvic residual to the experimentally determined handlebar and seat equivalent. Plots are provided for an arbitrary three cycles of the first trial of each participant and are arranged by load type and direction (e.g. S-I force or M-L moment). All forces are normalized by rider weight and all moments are normalized by rider weight and height. Data for each rider are shown on separate plots in order to increase readability. Note that RRA results tend to be more accurate for forces than moments. Also note that directions that see higher loading tend to show better results as well. This is likely due to the higher signal to noise ratio in these channels. Results for a given load direction tend to vary as well between participants. Some load directions, such as S-I force, show uniformly reasonable results across all participants while others, such as S-I moment, show varying results from participant to participant. One final point to note is that the choice to display data for the first trial was done arbitrarily without any regard to the quality of the data relative to the other two trials. Trial 1 of participant 2018July13-01 (Shown as July13 in figures J.1 thru J.6) showed some of the best correlation between RRA and HBSE while trial 1 of 2018Nov09-01 (Shown as Nov09 in figures J.1 thru J.6) showed some of the worst correlation.

Figure J.1: Three cycle RRA and HBSE anterior-posterior force comparison.

Figure J.2: Three cycle RRA and HBSE medial-lateral force comparison.

Figure J.3: Three cycle RRA and HBSE superior-inferior force comparison.

Figure J.4: Three cycle RRA and HBSE anterior-posterior moment comparison.

Figure J.5: Three cycle RRA and HBSE medial-lateral moment comparison.

Figure J.5: Three cycle RRA and HBSE superior-inferior moment comparison.

Appendix K. Bike Pedal Marker Cluster Update

The HMBL utilizes an exercise bicycle that is equipped with force transducers on each pedal in order to measure the loads applied to a rider's foot during cycling. However, because the pedals and load cells move through space when in use, they require a tracking object to mark their location. This object consists of a cluster of markers attached to the pedal. Prior to this study, the marker cluster was made up of four markers attached to a wooden frame and taped to the pedal. Figure K.1 shows the pedal assembly with attached load cell, pedal cluster frame, and markers.

Figure K.1: Model of instrumented left pedal with marker cluster frame and four markers. The offset from the marker cluster origin to the center of the load cell top surface is shown in local coordinates.

Wood as a frame material was not ideal because it moved with respect to the pedal and load cell when bumped or during fast pedaling. Additionally, the wood naturally warped over time, exacerbating the issue. Misalignment of the tracking object and the load cell led to misapplication of the pedal forces in post processing and poor overall kinematic results.

In order to ensure that the loads from the force transducers are applied in the correct position, the exact offset between the load cell electrical origin and the marker cluster must be known. Figure K.1 shows how the offset can be determined off of an engineering model. The center of the top of the load cell is the starting point used by the manufacturer to define the load cell's origin and differs from transducer to transducer. Because the measurement between the load cell top center and origin marker could only be done accurately in CAD, it was imperative that the marker cluster frame be dimensionally accurate to the model. To meet these tolerance requirements as well as to ensure stability over time, the frame was fabricated from 0.2 inch steel plate using a high precision water jet cutter. Figure K.2 below shows a rough cut marker cluster frame straight off of the water jet.

Figure K.2: Water jet cut steel marker cluster frame.

This manufacturing method was capable of cutting both the rough shape and the mounting holes of the frame in a single pass. This reduced the likelihood of hole misalignment and resulted in a more reliable part. To further increase the accuracy of the frame location, one of the attachment points was designed as a slotted hole. This allowed the frame to be installed perfectly parallel to the axis of the pedal.

With the new marker cluster frame completed, two UNC 6-32 holes were drilled and tapped into the pedal. To reduce the chance of reflections that could interfere with motion capture, the pedals and

frames were painted matt black. The frame and markers were then mounted to the pedal taking extra care that the markers were correctly located on the frame. Figure K.3 shows the completed pedal assembly.

Figure K.3: Assembled redesigned pedal with steel frame and bolted interface.