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Force Production Asymmetry in Males and Females During Three Variations of a Countermovement Push-up

By

Taylor M. Walston

Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

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<u>**Master's Thesis**</u>

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Taylor M. Walston

05/18/2023

Force Production Asymmetry in Males and Females During Three Variations of a Countermovement Push-up

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

by
Taylor M. Walston
May 2023

Abstract

Kinetic asymmetry analysis is a prevailing topic within human performance and rehabilitative science. So far focused on lower extremity functional tasks, these pioneering research methodologies remain unapplied to the upper extremity. Relative to its popularity, research on push-up asymmetry is limited, with sub-maximal variation and sex-based comparisons few. A paucity of research exists utilizing innovative asymmetry analysis strategies in the upper extremities. Study objectives were three-fold: (1) evaluate vertical ground reaction force (vGRF) asymmetry across push-up variations stratified by force demand, (2) compare asymmetry across sexes, (3) and contribute novel, normative asymmetry data to the existing pool of research findings. Participants (10 female, 17 male) performed three variations of push-up while left and right upper extremity vGRF's were independently recorded. Absolute asymmetry values of force-time derived measures of pushing force were then calculated. No statistically significant effect of variation or sex was shown across measures apart from braking impulse asymmetry and starting position weight distribution asymmetry where a main effect of sex was shown (p <0.05; ηp^2 = 0.179-0.203). Differences were generally small (< 1.5%) between variations and groups. Individualized participant asymmetry magnitudes were generally less than 5% with evident lack of consistency in left-right bias across measures and variations. Consistent with literature, push-up asymmetry profiles more individualized than sex or variation specific. Normative data contributions of <5% pushing force asymmetry expected in an asymptomatic cohort. Individuality and high variability of asymmetry is likely more critical than group, sex, or variation effects, emphasizing need for longitudinal, individualized assessment strategies.

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Introduction

The body weight push-up has remained ubiquitous in strength training, rehabilitation and performance assessment through not only plain efficacy, but due to its adaptability and simplicity as a testing and training tool (Harman et al., 2008; Harrison, 2010). This flexibility permits exercise tailoring, allowing for the targeting of particular tissues and desired intensity levels, thereby achieving precise training and rehabilitation outcomes or specificity in performance testing (Ebben et al., 2011; Lunden et al., 2010; Suprak et al., 2011; Wood et al., 2009; Wood & Baumgartner, 2004). Often, the emphasis when tracking training improvements or completing performance testing are upper extremity vertical ground reaction force (vGRF)-derived measures such as peak vGRF ($vGRF_{peak}$) and rate of force development (RFD) as approximate performance estimations for shoulder strength and power (Fanning et al., 2021; Hogarth et al., 2013; Parry et al., 2020; Zalleg et al., 2020).

Due to its structure and freedom of movement, the glenohumeral joint is inherently unstable relative to many joints in the body (Lear & Gross, 1998). Improper positioning of the humeral head in relation to the scapula, seen commonly in highly flexed and elevated shoulder positions, creates the possibility for unhealthy joint reaction forces to occur when under load (Decker et al., 1999; Lear & Gross, 1998). Through combinations of kinematic, kinetic and electromyographical (EMG) analysis, a push-up difficulty hierarchy has emerged, with steps up from modified to traditional and then the maximum push-up test corresponding to larger experienced vGRFs and increased muscular activation across the upper extremity (Decker et al., 1999, 2003; Ebben et al., 2011; Gouvali & Boudolos, 2005; Hinshaw et al., 2018; Koch et al., 2012; Marcolin et al., 2015; Parry et al., 2020; San Juan et al., 2015; Suprak et al., 2013, 2011). Utilized primarily as a performance test, the maximum push-up (MAX) is a single repetition explosive movement which elicits higher peak forces than the traditional submaximal countermovement push-up (TRAD), with the modified on-knees push-up (MOD) eliciting the lowest upper extremity vGRF values of the three (Hinshaw et al., 2018; San Juan et al., 2015). EMG findings support this trend, with both the prime movers (pectoralis major and triceps brachii) and scapular stabilizers (serratus anterior, upper trapezius and lower trapezius) showing a smaller magnitude of activation during the MOD compared to the TRAD, along with a relative lower percent of body weight supported throughout the entire range of motion (Gouvali & Boudolos, 2005; San Juan et al., 2015).

Kinematic analysis of the scapula during variations of the push-up, paired with EMG assessment of scapular stabilizers, suggests that when moving to a relatively more difficult variation, a higher risk of improper scapular positioning is possible (Decker et al., 1999; Lear & Gross, 1998; Ludewig et al., 2004; Lunden et al., 2010; San Juan et al., 2015; Suprak et al., 2013). As load increases, relatively weaker stabilizers may not be able to effectively match the activity of stronger antagonist muscles, which could in turn allow the scapula to move out of its properly aligned and healthy position jeopardizing shoulder health (Ludewig et al., 2004; Suprak et al., 2013). Task difficulty, however, is relative to the individual in question and more precisely, to each individual limb. Imbalanced capabilities due to injury or baseline performance may therefore create unilaterally asymmetrical risk. Asymmetry analysis on both a population-wide and individual level is critical for appropriate exercise prescription. Without accurate and complete normative biomechanical profiles of these exercises, practitioners planning to make use of the push-up will remain inadequately guided.

A common goal within push-up research is the development of normative metrics which will guide rehabilitation and training practices in the field (Dai et al., 2019; Fanning et al., 2021;

Li et al., 2021; Poploski et al., 2020). A potential problem with the relationship between the push-up exercise and rehabilitation is the frequent unilateral nature of injury, possibly limiting the rehabilitative and performance testing utility of the bilateral push-up. To date, several attempts have been made to research the extent of vGRF asymmetry that is experienced across the upper extremities during push-ups (Dai et al., 2019; Fanning et al., 2021; Koch et al., 2012; Li et al., 2021; Parry et al., 2021; Poploski et al., 2020). So far, these asymmetry analyses have only been conducted featuring the MAX. This single repetition explosive task has been compared to the functionally similar countermovement jump test commonly utilized for evaluating lower extremity asymmetries in strength and power (Bailey et al., 2015; Bell et al., 2014; Bishop, Turner, et al., 2018). The results of these formerly mentioned push-up studies, which investigated individuals from a wide variety of backgrounds, generally showed a relatively small degree of average group asymmetry < 3% towards the self-selected "preferred limb". Limb preference in these cases being defined as the limb, right or left, which a participant would elect to complete a unilateral task with, such as throwing a ball. In these studies, indices of asymmetry were commonly calculated as the percent difference between the self-reported preferred and non-preferred limb across various force-time derived measures related to strength and power, such as peak vGRF, peak RFD and eccentric and concentric phase specific impulses.

When performing a MAX, NCAA Division 1 male and female athletes from 14 different sports experienced pushing force asymmetries of generally less than 10% towards the non-dominant or dominant side for those between the 10^{th} and 90^{th} percentile respectively (Dai et al., 2019). Furthermore, no group interaction between sport participation and degree of asymmetry experienced was shown, even between unilateral overhead and non-overhead sporting groups. While this lack of preferred side pushing force asymmetry was echoed in a similarly designed investigation of male collision athletes during group analysis (~ 0%), there was a degree of absolute asymmetry found (Fanning et al., 2021). When absolute percentage differences were calculated between limbs for each participant and averaged for the group, larger differences of ~4% were reported. A possible implication of this finding is that preference based, arbitrary limb assignment may washout and disguise absolute inter-limb asymmetry present on an individual level.

Lower extremity asymmetry researchers have worked to address this possible washout effect by emphasizing the individualized and task specific nature of asymmetry when designing studies. The choice in formula used to calculate asymmetry, as well as the decision making particulars regarding the classification and organization of limbs into groups have been previously discussed at length due to their considerable effect on outcome measures and the perception of findings (Bishop et al., 2016, 2021; Bishop, Read, et al., 2018; Dos'Santos et al., 2021; Exell et al., 2012; Parkinson et al., 2021; Virgile & Bishop, 2021; Zifchock et al., 2008). Limb classification methodologies, such as using right and left anatomical side, preferred and non-preferred limb, objectively measured stronger and weaker limb, as well as injured and uninvolved side, have all been utilized for the purpose of standardizing limb assignment amongst participants (Bishop et al., 2016; Parkinson et al., 2021). Asymmetry outcome measures calculated based on percent differences between these limb groups are subject to change depending on the classification strategy chosen. Limb preference, subjectively determined by the participant or the observer, has been shown to not always predict limb dominance (Kuki et al., 2019), which is objectively determined by the particular outcome measure and tests chosen (Bishop et al., 2020). A thorough understanding of the differences between an objectively measured strength-based dominant limb and subjectively selected limb preference, as well as how that assignment may affect a calculated percentile difference between limbs, is crucial for not only consistent and accurate reporting across studies, but for creating useful normative data, as well (Parkinson et al., 2021).

In addition to the limitations created by arbitrary limb group assignment, to the best of the authors' knowledge, there are no studies to date which have attempted to measure submaximal push-up kinetic asymmetry featuring either the TRAD or MOD. Additionally, only two studies investigating push-up kinetic asymmetry have included female participants (Dai et al., 2019; Li et al., 2021). While some research indicates that female subjects produce forces significantly more asymmetrically than males in lower extremity tasks (Bailey et al., 2015), conflicting reports suggest no significant difference (Bell et al., 2014; Fort-Vanmeerhaeghe et al., 2020). Also unclear is whether the difference in observed asymmetry was precipitated by a genuine difference between sexes, or perhaps absolute strength alone. This question raised by the finding that once groups were delineated by absolute strength irrespective of sex, larger magnitude differences in asymmetry were reported (Bailey et al., 2015).

Without a complete understanding of the baseline asymmetry expected in healthy individuals, practitioners will be hard-pressed to accurately and reliably identify abnormal strength and performance imbalances in the field. Baseline profiles of force asymmetry among healthy subjects that account for the individualized and task-specific nature of these measures are needed to determine the existence of asymmetry, and if present, to what extent it should be expected.

Therefore, the purpose of the current study was to investigate the effect of push-up exercise variant (TRAD, MOD and MAX) and participant sex on the kinetic asymmetry between the left and right upper extremity during a push-up. We hypothesized that push-up task difficulty would have a significant effect on asymmetry, with higher relative kinetic demand precipitating increased kinetic asymmetry in two discernable ways. The first, was that the MOD would elicit less asymmetry than the TRAD, with the MAX displaying significantly more kinetic asymmetry than both sub-maximal variants. Sex was also hypothesized to have a significant effect on asymmetry, with females expected to show significantly greater kinetic asymmetry than males due to an expected sex-based disparity between groups in upper-extremity force generation capacity leading to a higher relative kinetic demand for female participants.

With these findings, a better understanding of push-up kinetics in healthy populations was to be established, providing rehabilitation practitioners, strength and conditioning specialists and future researchers more accurate and precisely defined normative data for use in the field.

Materials and Methods

Description of study sample. Participants included a convenience sample of male and female volunteers recruited at Western Washington University. Exclusion criteria consisted of a previous history of upper extremity injury requiring surgery or rehabilitation, or an inability to complete 5 consecutive traditional pushups without loss of form or without pain. Written informed consent was acquired from all participants before study participation. Approval for this study was granted by the University Institutional Review Board.

Instrumentation. All data collection took place in the Motion Analysis Laboratory at Western Washington University. Participant standing height was collected using a standard stadiometer. vGRFs during push-up trials were collected for each hand separately via two adjacent AMTI Gen 5 force platforms embedded in and flush with the floor (Advanced Mechanical Technology Inc., Waterton, MA, USA). Participant total body weight was collected during a standing static trial. Kinematic data across the push-up range of motion for each trial was collected via a 10-camera motion capture system (Vicon, Vantage V8, Centennial, Colorado, USA) which collected data from one retroreflective marker placed with double sided adhesive on the skin over the spinous process of the 7^{th} cervical vertebrae (C7). The two force platforms and camera system were interfaced and synchronized with Vicon Nexus Software (Vicon Nexus version 2.14, Centennial, Colorado, USA). Collection frequency for the force plate and cameras were set to 1000 Hz and 100 Hz, respectively.

Experimental procedures. All testing was completed during a single session lasting approximately one hour. Upon arrival, participants completed a consent form and answered questions for the purpose of determining inclusion in the study. Participant height and mass were then collected. The C7 spinous process was then palpated, and a retroreflective marker placed over it via double-sided tape. Consistent with previous research by Fanning et al. (2021), this C7 marker was utilized for the purpose of determining push-up depth during each repetition (i.e., when the participants reached the bottom of the push-up vs. the top).

All participants then completed a standardized bilateral warm-up procedure consisting of both Codman's pendulums and rotator cuff stretching similar to protocols used previously (San Juan et al., 2015; Suprak et al., 2011). Participants were then instructed to assume a traditional push-up position similar to that described in Suprak et al. (2013), with weight on hands and feet, hands placed separately on each adjacent force platform directly underneath the shoulder, knees and feet together, maintaining an angle of 180º between the upper and lower body. In this posture, a self-selected inter-hand width was then chosen by the subject to be used in all trials (Fanning et al., 2021; Koch et al., 2012). Subjects were encouraged to assume a familiar inter-hand width which they would elect to use during self-directed training. This method was utilized to replicate push-up positioning which participants might regularly experience during real-life training. Participants were instructed to align the midline of their body with a small horizontal gap between force platform one and two (to be aligned with the superoinferior direction of the subject's body) and place their hands equidistant from this gap.

The superoinferior and mediolateral position of both hands was then marked with a tape to provide participants with a hand placement reference to ensure repeatability between trials and conditions. Participant foot position was then marked with a mediolateral strip connecting both foot contact points placed perpendicularly to a tape line extending from and square to the gap between force platforms. This marked position represented the traditional starting posture.

To establish the modified starting posture, participants were instructed to lower their knees to the ground from the traditional starting posture without moving their feet. Participants were then asked to lift their feet off the floor while keeping their feet and ankles together. This new lower body base of support was then marked with a horizontal strip of tape at the knees in the same manner as the feet. Hand positions were consistent for all three conditions, with foot and knee contact points used for the traditional and modified starting postures, respectively.

Participants were then familiarized with three push-up variations. Participants performed a minimum of five practice push-ups in each of the three variations during this time while being simultaneously familiarized with the collection procedures.

MAX collection procedures were based on protocols described by Fanning et al. (2021). After assuming the traditional starting posture, a verbal countdown was given, followed immediately by a single maximal effort countermovement push-up. This movement begins with a descending phase, with elbow flexion as the body lowers, followed immediately by an explosive maximal effort ballistic press-up away from the floor with the goal of achieving lift-off from the ground. Participants were instructed to maximally extend their elbows as their hands broke contact with the floor, with their feet remaining in contact with the ground throughout. Participants were instructed to push as hard and as fast as possible during the ascending phase with the goal of achieving maximal trunk flight height above the floor. No cues determining landing technique were provided.

TRAD and MOD trials each consisted of three consecutive repetitions using the same general testing protocol, differentiated by a distinct starting posture for each condition (i.e. traditional and modified). To begin each trial, participants assumed the respective starting posture followed by a three second verbal countdown. Participants then immediately began to perform push-up repetitions in a steady continuous fashion and at a self-selected pace. Participants began by lowering themselves to a self-selected terminal depth followed immediately by extension away from the floor back to the original starting posture. This completed repetition was immediately followed by the second and third repetitions. At the end of the third repetition, participants re-assumed the starting posture and paused, holding until instructed to rest by the researcher.

Throughout each condition, participants were instructed to complete each movement while maintaining an angle of approximately 180º between the upper and lower body. Participants were afforded a rest period of at least 1 minute between trials. Self-selected pacing and terminal depth were chosen to further ensure that the performance of the exercise resembled that of a familiar and comfortable push-up for each individual subject to appropriately capture their natural push-up profile. Self-selected pacing was shown previously to change only minimally across changing push-up conditions, suggesting that constraints placed on pace may not be necessary as a control (Lear & Gross, 1998). In the current study, this anticipated small variation in pacing was considered justifiable to help maintain the integrity of each participant's natural push-up profile. After completion of the testing session, participants were provided debriefing information as to the purpose of the study. Only at the conclusion of data collection were participants informed that asymmetry was being analyzed. Participants were then asked to self-report which arm they would elect to complete a throwing task with.

Data processing. Data filtering for C7 marker trajectories, as well as vGRF data from each force plate was completed in Vicon Nexus (Vicon Nexus version 2.14, Centennial, Colorado, USA) using a 4th order zero-lag, low-pass Butterworth filter with cutoff frequencies of 15 Hz (Fanning et al., 2021) and 50 Hz (Sha & Dai, 2021) for the kinematic and kinetic data, respectively. Filtered data was then exported, processed, and compiled in MATLAB (The MathWorks, Inc., Natick, MA, USA) using custom MATLAB script (Appendix B) to isolate repetitions and phases of interest for analysis.

For the MAX, a complete repetition was defined as the period between the initiation of downward motion at the beginning of the eccentric phase and the instant of take-off from the ground at the end of the concentric phase. The start was identified by a negative change in total summed left and right vGRF > 5% of the average total summed vGRF recorded during a one second period before the start of the repetition (Meylan et al., 2010). Take-off was identified as the time point where total vGRF of both the left and right forces was < 10 N (Sha & Dai, 2021). MAX repetitions were then delineated into three discrete phases. Two of these phases occurred during the downward motion of the push-up defined as the un-weighting acceleration phase at the beginning of downward movement, followed by the eccentric deceleration phase during the period of braking before reaching the bottom of the countermovement (Fanning et al., 2021; Jordan et al., 2015). These two phases were separated by an acceleration inflection point, occurring at the instant of deceleration, calculated as the instant of peak negative vertical velocity of the C7 marker. The third phase is one of concentric acceleration, beginning at the instant of positive vertical velocity at the bottom of the countermovement and ending with takeoff, identified as the time point where total vGRF of both the left and right forces was < 15 N (Sha & Dai, 2021)

For the TRAD and MOD trials, a complete repetition was defined as the time between the period of initial downward countermovement and the point where C7 vertical position returns to rest at the end of the concentric phase. TRAD and MOD repetitions were then divided into four phases with the first three defined and extracted in the same way as the maximum push-up trials with the exception that in the TRAD and MOD trial, the concentric acceleration phase ended at the point of greatest positive vertical C7 marker velocity. The end of this third phase marks the beginning of an additional fourth and final phase defined as a period of concentric deceleration, when deceleration begins as the body returns to rest at the completion of the repetition.

TRAD and MOD trials consisted of 3 continuous repetitions with the second repetition used for analysis. This design was implemented to ensure participants were performing the push-up task as naturally as possible during the analysis window by lessening the impact that the physical and mental impetus of beginning a repetition from a static position could have on their technique. In this way, data would be captured during a period with more stabilized form. This approach was inspired by similar techniques utilized previously in sprint asymmetry research which allowed multiple gait cycles to occur before collection (Exell et al., 2017).

Data analysis. All computations were completed in MATLAB using a custom MATLAB script (Appendix B). Separate right and left limb eccentric deceleration and concentric acceleration phase specific impulses were calculated by time integration of the force-time curve for the repetition of interest in each trial. A separate peak vGRF under the right and left hand was calculated over the entire repetition of interest for each trial. Additionally, right and left side initial weight supported was collected from a one second quiet period before the beginning of each TRAD and MOD push-up trial. For the MAX, independent left and right mean RFD was calculated as the difference in maximum and minimum vGRF recorded, divided by the time elapsed between those events. Left and right independent eccentric deceleration peak RFD and concentric acceleration peak RFD represented the largest magnitude change in vGRF expressed during any ten-millisecond period within the relative phase, with that value being divided by ten milliseconds to resolve peak RFD as a value.

Independent variables included in the current study were participant sex and push-up variant. Dependent variables for the TRAD and MOD push-up conditions were absolute bilateral asymmetry indices (BAI_{ABS}) between the left and right side for peak vGRF, eccentric deceleration phase impulse, concentric acceleration phase impulse and initial weight supported. Dependent variables for the MAX were BAI_{ABS} for peak vGRF, eccentric deceleration phase impulse and concentric acceleration phase impulse as well as BAI_{ABS} for mean RFD, eccentric deceleration peak RFD and concentric acceleration peak RFD.

Previous asymmetry studies have utilized a wide assortment of calculation techniques to produce asymmetry scores. Based on recommendations from previous reviews of these methods (Bishop et al., 2016; Bishop, Read, et al., 2018; Dos'Santos et al., 2021; Parkinson et al., 2021) and due to the bilateral nature of the push-up task, the BAI was chosen to calculate asymmetry as a difference between values recorded for both limbs relative to the sum of both values. BAI was calculated for each dependent variable as follows:

$$\text{BAI (\%)} = \frac{\text{right limb measure} - \text{left limb measure}}{\text{right} + \text{left limb measure}} \cdot 100$$

where positive values refer to right-sided asymmetry, and negative values refer to left sided asymmetry. Participant BAI results for each dependent variable were then averaged across trials before taking the absolute BAI (BAI_{ABS}) for each participant. This order of operations was chosen to preserve the between-trial directional variability of asymmetry within-subjects.

Statistical analysis. Computed values were exported to SPSS (SPSS; V28.0.1.0; SPSS, Inc., Chicago, IL, USA) where all statistical analysis was completed. Custom written SPSS syntax and complete statistical output shown in Appendix C. A single two-way mixed analysis of variance (ANOVA) was used to assess the effect of push-up starting posture (traditional vs. modified) and participant sex (male vs. female) on weight distribution (WtD) BAI_{ABS}. Three additional two-way mixed ANOVA's were conducted to determine the effect of push-up variant (MOD vs. TRAD vs. MAX) and participant sex (male vs. female) on BAI_{ABS} values for peak vGRF, eccentric deceleration impulse, and concentric acceleration impulse. For the four ANOVA's, Mauchly's test was used to assess the assumption of sphericity, with Greenhouse-Geisser corrections used in the case of test violation. Levene's test was used to assess the assumption of equal variance. Simple effects analyses were conducted for any significant interaction effects, with Tukey post-hoc procedures conducted in the case of significant main effects without interaction. Power related BAI_{ABS} for the MAX (mean RFD, eccentric deceleration peak RFD, and concentric acceleration peak RFD) were compared between male and female groups using t-tests ($p < 0.05$).

To help visualize the individualized nature of asymmetry, a bar chart was created for each dependent variable based on an amalgamation of previous recommendations (Bishop et al., 2021; Dos'Santos et al., 2021; T. A. Exell et al., 2012). Average bilateral asymmetry index values for each subject were charted as either positive or negative bars along the x-axis with their y-axis asymmetry value dependent on the magnitude and direction of asymmetry for the relevant dependent variable. For each chart, population mean + smallest worthwhile change: (SWC) (0.2 · between-subject SD) and population mean + population standard deviation (SD) was then calculated and graphed as a pair of horizontal lines above and below the x-axis as positive and negative asymmetry thresholds. These threshold pairings work together to create a population specific hierarchy of "small to moderate" to "high or extreme" degrees of asymmetry respectively. This helps to visualize and showcase individual participant asymmetry profiles relative to the entire study population.

Results

Participant characteristics are shown in Table 1. Male participants were found to be significantly taller ($p < 0.001$), heavier ($p < 0.01$) and older ($p < 0.5$) than female participants. Only 2 of the 27 included participants expressed a left-hand throwing preference, both of which were male.

For starting position WtD BAI_{ABS}, no statistically significant interaction effect was shown between sex and variation ($F[1,25] = 0.730$, $p = 0.401$, partial $\eta^2 = 0.028$, observed power = 0.130). There was also no significant main effect of variation shown ($F[1,25] = 1.308$, $p = 0.264$, partial $\eta^2 = 0.050$, observed power = 0.196). A main effect of sex was found, however, with female participants showing a significantly higher degree of absolute asymmetry in vGRF in the starting postures ($F[1,25] = 6.373$, $p = 0.018$, partial $\eta^2 = 0.203$, observed power = 0.680). Levene's test showed that group variances were not equal for the traditional posture ($F[1,25] = 5.269$, $p = .030$), thus group differences should be interpreted with caution. Descriptive statistics for WtD asymmetry are displayed in Table 2.

Descriptive statistics and ANOVA results for peak vGRF BAI_{ABS}, eccentric deceleration impulse BAI_{ABS}, and concentric acceleration impulse BAI_{ABS} are shown in Table 3. ANOVA findings showed no significant interaction between the effects of participant sex and push-up variation, nor any significant main effect of variation on these vGRF asymmetry measures. For participant sex, a significant main effect was found for eccentric deceleration impulse BAI_{ABS} ($F[1,25] = 5.455$, $p = 0.028$, partial $\eta^2 = 0.179$, observed power = 0.612), but not for peak vGRF BAI_{ABS} or concentric acceleration impulse BAI_{ABS}.

Figures 2-5 each display individual participant BAI results across push-up variations, with each figure relating to a specific dependent variable. Bars extending in the positive direction demonstrate asymmetry which favors the participants right limb whereas negative bars relate to left-sided dominance. The two pairs of horizontal lines above and below the x-axis relate to asymmetry thresholds calculated from the means and standard deviations taken from the average absolute BAI of all subjects across all conditions for the relevant dependent variable.

Figure 6 shows individual MAX variation BAI results for the power related variables of mean RFD, eccentric deceleration peak RFD and concentric acceleration peak RFD. Asymmetry thresholds were calculated in the same manner as Figures 2-5.

Table 1. Demographic information for all participants (n=27) as well as male (n=17) and female (n=10) groups.

	Male	Female	Combined
Age (yrs)	21.94 ± 2.02*	20.30 ± 1.06*	21.33 ± 1.85
Height (m)	177.40 ± 5.22*	164.53 ± 4.08*	172.63 ± 7.77
Mass (kg)	82.46 ± 13.95*	65.92 ± 11.22*	76.34 ± 14.87

Values shown as mean ± sd.

* denotes significant difference between sexes ($p<0.05$)

Table 2. Comparison of male and female absolute upper extremity weight distribution (WtD) asymmetry in the modified and traditional push-up starting postures.

	Male	Female	Combined
Modified WtD BAI_{ABS} (%)	3.27 ± 2.29	4.46 ± 3.20	3.71 ± 2.67
Traditional WtD BAI_{ABS} (%)	1.79 ± 1.49	4.25 ± 3.72	2.70 ± 2.76
Combined WtD BAI_{ABS} (%)	**2.53 ± 1.81 †**	**4.36 ± 1.82 †**	

Values shown as mean ± sd.

† denotes significant main effect of sex

Table 3. Comparison of male and female push-up kinetic BAI_{ABS} (%) across variations.

		Eccentric deceleration phase impulse	Concentric acceleration phase impulse	Peak force
MOD	Male	2.25 ± 1.36	1.95 ± 1.57	2.31 ± 1.82
	Female	1.60 ± 1.02	1.42 ± 0.90	1.14 ± 0.75
	Total	2.01 ± 1.27	1.75 ± 1.37	1.88 ± 1.60
TRAD	Male	2.15 ± 1.17	1.75 ± 1.42	2.11 ± 1.68
	Female	0.78 ± 0.69	1.99 ± 1.93	1.60 ± 1.05
	Total	1.64 ± 1.21	1.84 ± 1.60	1.93 ± 1.47
MAX	Male	1.91 ± 1.62	1.93 ± 1.29	2.16 ± 1.62
	Female	1.66 ± 1.38	2.70 ± 2.51	2.55 ± 2.52
	Total	1.82 ± 1.52	2.21 ± 1.83	2.30 ± 2.00
Interaction effect		p=0.271 (0.051)	p=0.117 (0.082)	p=0.126 (0.086)
Main effect of variation		p=0.394 (0.037)	p=0.128 (0.079)	p=0.203 (0.064)
Main effect of sex		***p*=0.028 (0.179) †**	p=0.773 (0.003)	p=0.422 (0.026)

Values shown as mean ± sd.
(ηp^2) = partial eta squared
† denotes significant main effect

Table 4. Comparison of male and female power related variables during the MAX.

	Mean RFD BAI_{ABS} (%)	Eccentric deceleration phase RFD_{peak} BAI_{ABS} (%)	Concentric acceleration RFD_{peak} BAI_{ABS} (%)
Male	5.37 ± 5.76	6.48 ± 3.36	12.83 ± 6.26
Female	5.88 ± 6.15	6.69 ± 4.18	8.71 ± 6.47

Values shown as mean ± sd.

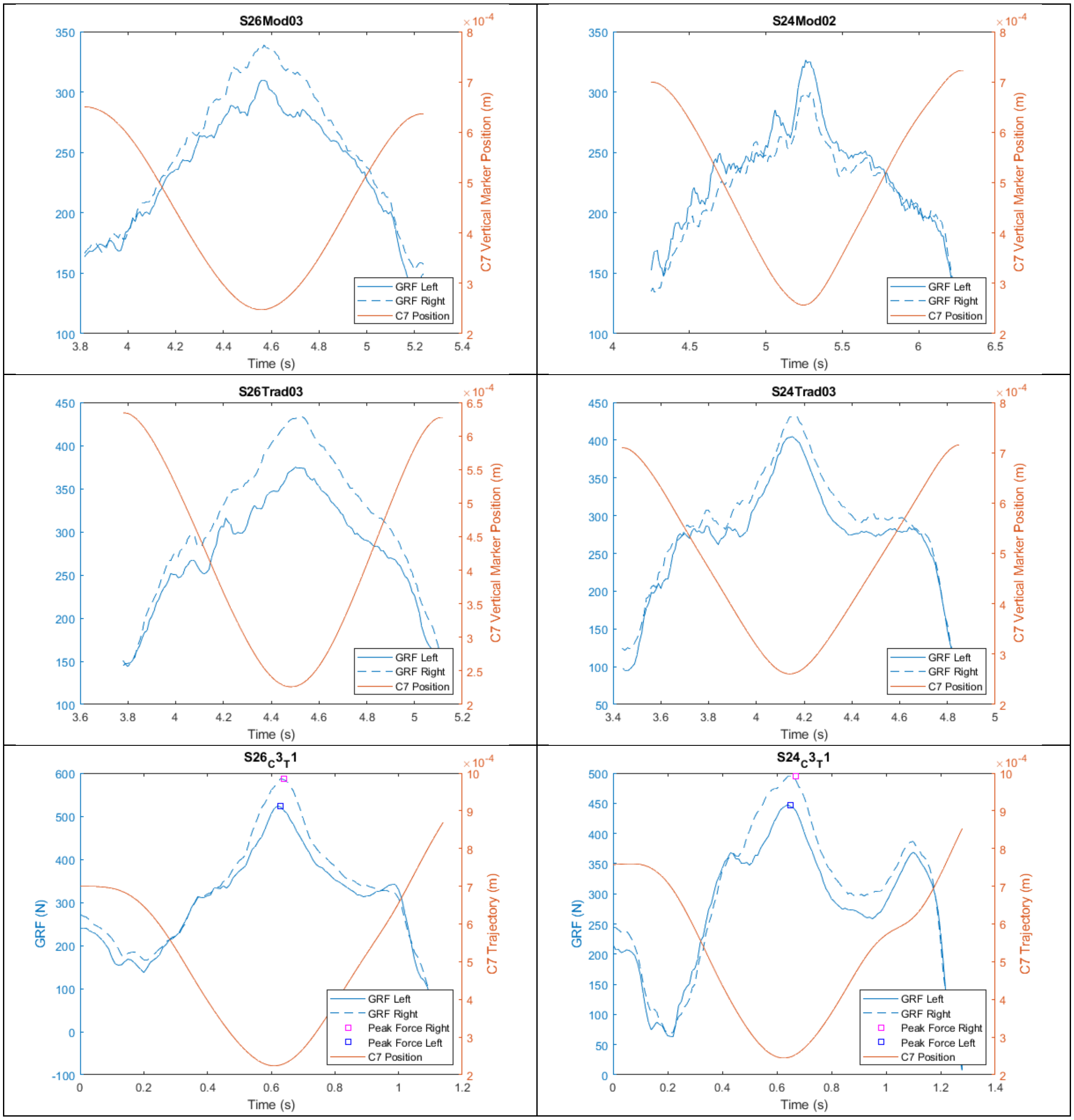

Figure 1. Examples of bilateral vertical ground reaction force (vGRF) traces from the left and right side during the modified (MOD), traditional (TRAD), and maximum (MAX) countermovement push-ups. Cervical spine retroreflective marker vertical displacement is also shown. Traces in the left column are from a participant who demonstrated consistent asymmetry favoring their right side across conditions and objective measures. Traces on the left feature a participant who showed a more variable profile, highlighted by the higher left sided vGRF in the MOD.

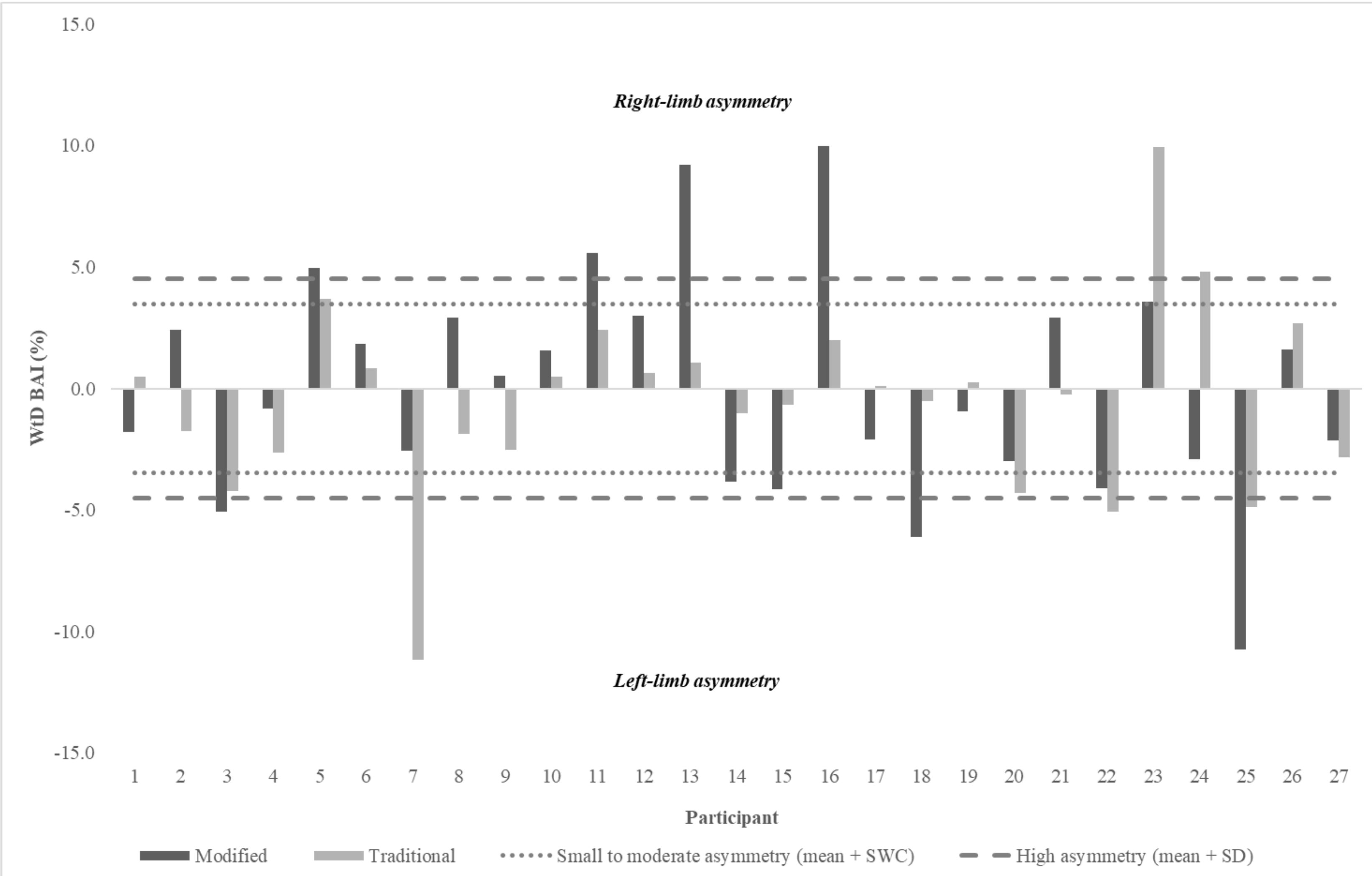

Figure 2. Individual participant starting position weight distribution (WtD) bilateral asymmetry index (BAI) results across the modified (on-knees) and traditional starting posture. Horizontal lines represent asymmetry thresholds specific to the study population, indicating relatively small to moderate asymmetry (population mean + smallest worthwhile change (SWC = SD*0.2)) and high asymmetry (population mean + SD).

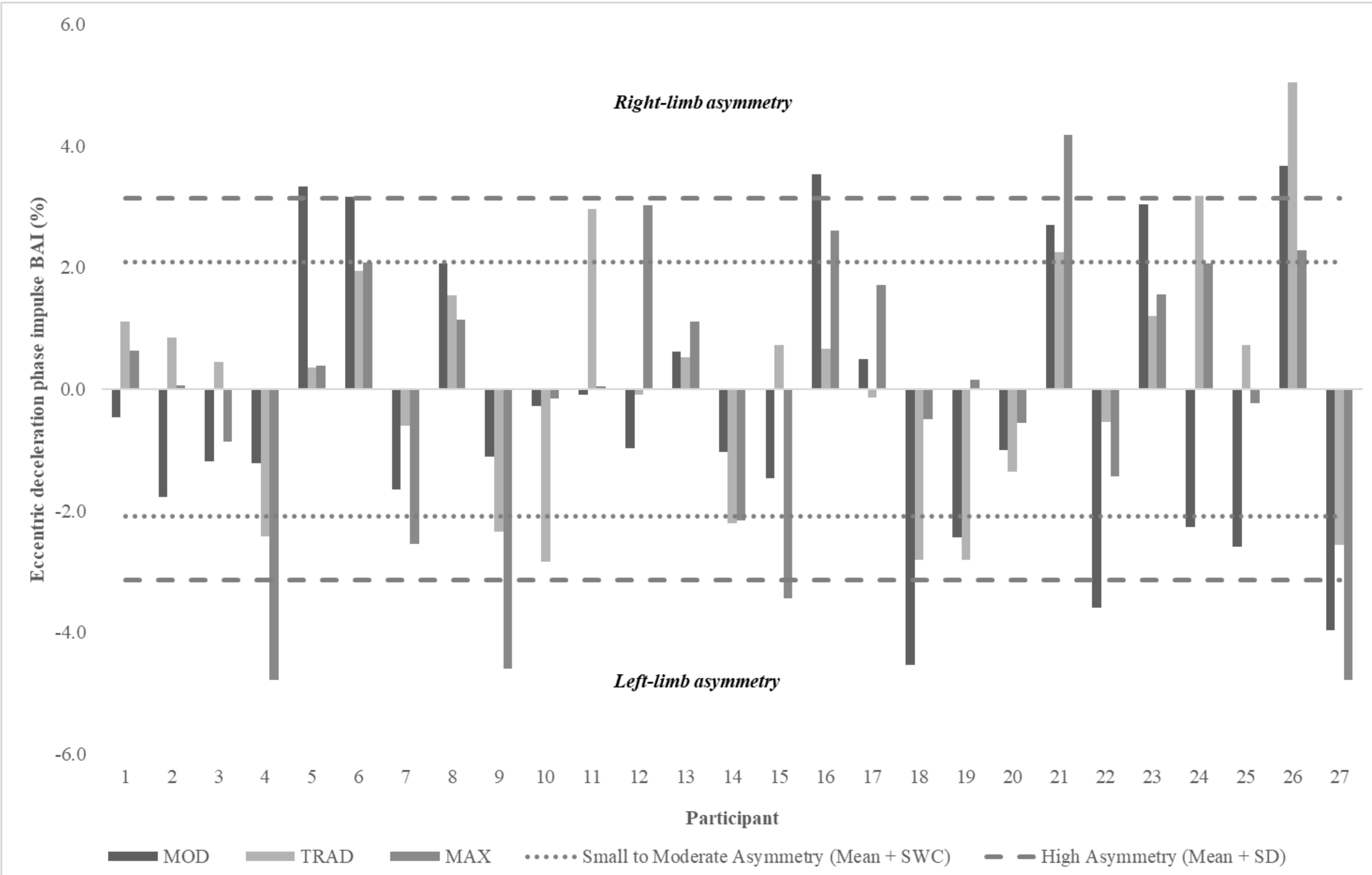

Figure 3. Individual participant eccentric deceleration phase impulse bilateral asymmetry index (BAI) results across the MOD, TRAD and MAX push up variations. Horizontal lines represent asymmetry thresholds specific to the study population, indicating relatively small to moderate asymmetry (population mean + smallest worthwhile change (SWC = SD*0.2)) and high asymmetry (population mean + SD).

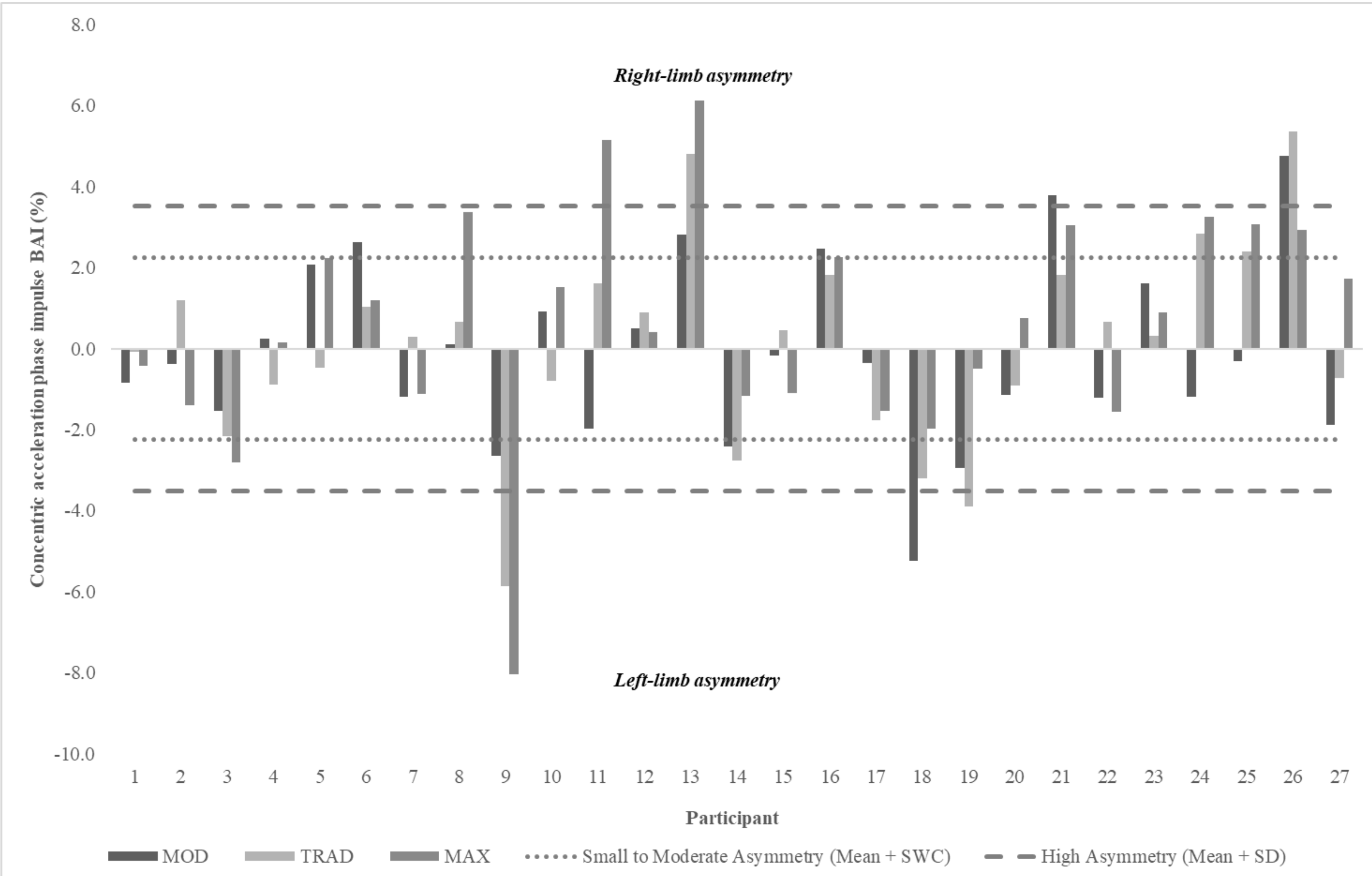

Figure 4. Individual participant concentric acceleration phase impulse bilateral asymmetry index (BAI) results across the MOD, TRAD and MAX push up variations. Horizontal lines represent asymmetry thresholds specific to the study population, indicating relatively small to moderate asymmetry (population mean + smallest worthwhile change (SWC = SD*0.2)) and high asymmetry (population mean + SD).

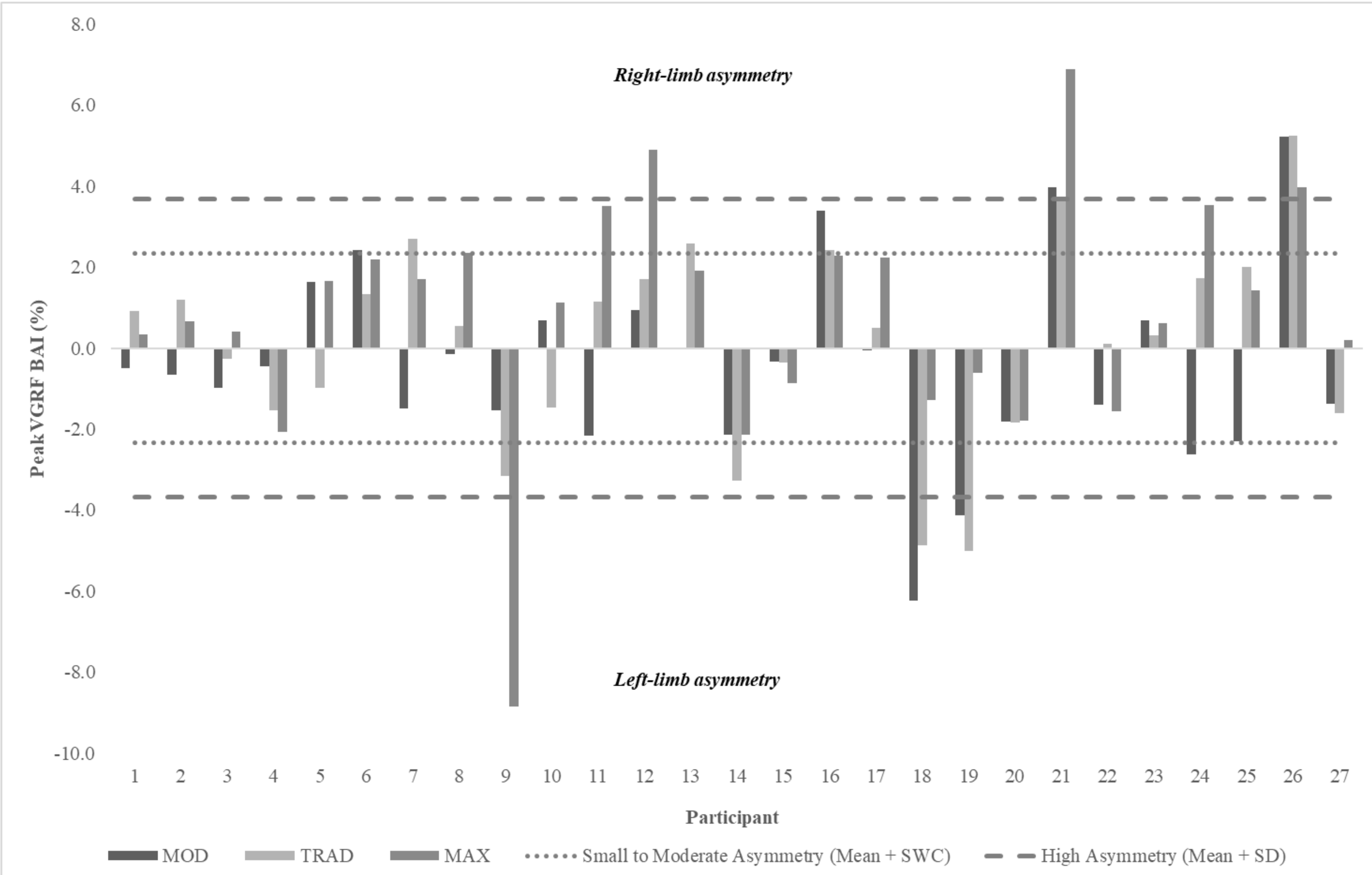

Figure 5. Individual participant peak vertical ground reaction force (vGRF) bilateral asymmetry index (BAI) results across the MOD, TRAD and MAX push up variations. Horizontal lines represent asymmetry thresholds specific to the study population, indicating relatively small to moderate asymmetry (population mean + smallest worthwhile change (SWC = SD*0.2)) and high asymmetry (population mean + SD).

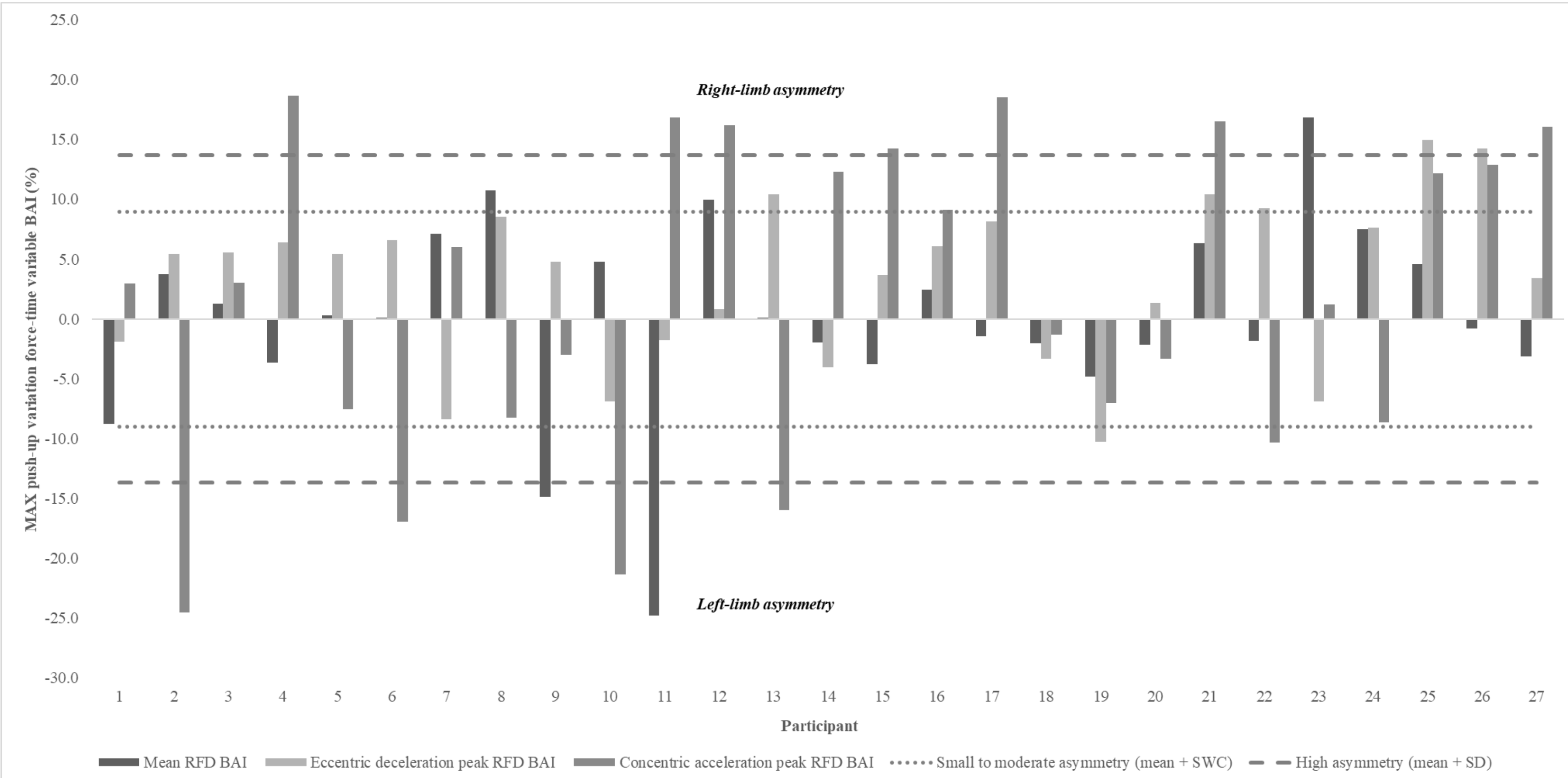

Figure 6. Individual participant bilateral asymmetry index (BAI) results during the MAX push-up variation for mean rate of force development (RFD) BAI, eccentric deceleration BAI and concentric acceleration BAI. Horizontal lines represent asymmetry thresholds specific to the study population, indicating relatively small to moderate asymmetry (population mean + smallest worthwhile change (SWC = SD*0.2)) and high asymmetry (population mean + SD).

Discussion

The current study included two experimental hypotheses, both largely predicated on a more generalized theory that increased relative push-up difficulty would elicit larger vGRF asymmetry in healthy participants. The first hypothesis was that force-demand differences between push-up types would have a significant effect on upper-extremity force asymmetry, with higher force demands (MAX > TRAD > MOD) resulting in increased absolute asymmetry in vGRF measures. The present findings demonstrate no significant effect of push-up type on the included pushing force asymmetry measures of peak vGRF, an instantaneous force measure, as well as both eccentric deceleration impulse and concentric acceleration impulse, which are summative measures of force application recorded over a period of time.

These findings were considered unexpected, in part because of the previously reported large differences in force demand between push-up variants which were expected to manifest variance in asymmetry between tasks. In similar cohorts as studied presently, peak vGRF during the sub-maximal MOD and TRAD have been shown to equate to 49-80% and 64-98% of participant standing body weight respectively with an approximately 12-20% body weight difference favoring the TRAD (Ebben et al., 2011; Hinshaw et al., 2018; San Juan et al., 2015). MAX push-ups, with their maximal effort pushing component, are reported to reach peak vGRF values as high as 94-131% body weight (Dhahbi et al., 2017, 2022; Hinshaw et al., 2018; Hogarth et al., 2013; Wang et al., 2017). These reported values create a vGRF based demand hierarchy between these three tasks with an approximately 15-30% body weight difference in expected peak vGRF between them. Due to the lack of previous investigations into the effect of push-up intensity on vGRF asymmetry, there is little existing data to which to compare the present findings. In lower extremity research however, there is mixed evidence to support a load by asymmetry relationship, with increasing load in the bilateral back-squat precipitating increased inverse-dynamics calculated ankle torque asymmetries (Kobayashi et al., 2010). This increase in load, however, did not lead to any statistically significant difference between sides in vGRF at the feet, indicating a possible disconnection between vGRF load balance and joint torque asymmetries. Evidence for this lack of a loading effect on vGRF asymmetry was further shown in another study evaluating the loaded barbell squat, with no significant difference in peak vGRF asymmetry between the 60% and 75% 1RM conditions (Sato & Heise, 2012). This stability in vGRF asymmetry across loads was echoed by the current push-up findings.

What remains unstudied, however, is the degree of shoulder and elbow joint torque asymmetry experienced during the completion of a push-up. Delineated joint torque symmetry analysis could paint a more accurate picture of the underlying mechanics of a push-up and provide more specificity during evaluations and research. Since a complete accounting of whole-body ground reaction forces is required for inverse dynamic calculations, joint torque analysis during push-ups becomes significantly more complicated than with standing tasks. The split base of support between the hands and feet necessitates the use of additional force platforms to capture all ground reaction forces acting on the system, while simultaneously increasing the computational load. The study design implications of these technical hurdles have been discussed at length with practical recommendations for how best to approach these problems (Dhahbi et al., 2022; Dhahbi, Chaouachi, Cochrane, et al., 2017; Sha & Dai, 2021). These considerations will be of supreme importance if inverse dynamics are to ever be soundly applied to push-up research. To minimize the effect of unaccounted for lower extremity forces, the current study instructed participants to keep their feet and knees together, centered on the midline. The intention was to limit lower extremity force lateralization, allowing for an assumption of bilaterally symmetrical force contribution by the lower body. This assumption allows for any difference seen in vGRF between force platforms under the hands to be levied exclusively to a bilateral upper-extremity force production disparity. Although relied on frequently by researchers, this assumption remains unconfirmed by testing. This likely due to the previously mentioned technological hurdles associated with incorporating additional force platforms into a study design. Barriers notwithstanding, there remains a need for a more delineated accounting of torque and force asymmetry during push-ups so that practitioners may better understand the complete force production profiles of those they are evaluating.

To the best of the author's knowledge, this is the first attempt to study vGRF asymmetry across both sub-maximal and maximum effort styles of push-up. Our MAX results compare favorably to existing literature on plyometric push-ups where vGRF derived pushing force asymmetry has been shown to generally fall under 4% (Dai et al., 2019; Fanning et al., 2021; Koch et al., 2012; Li et al., 2021; Poploski et al., 2020). These findings additionally support the broader trend for group calculated asymmetry indices in injury free cohorts to fall below the commonly described cutoff thresholds of 10% or 15%, where risk of injury or performance detriment has been shown to increase (Kyritsis et al., 2016; Parkinson et al., 2021). These asymmetry thresholds, while easy to remember and utilize in practice, have not proven to be consistently supported, with some researchers suggesting they should be avoided entirely (Parkinson et al., 2021).

Previous studies have found evidence alluding to a possible relationship between absolute strength and asymmetry, where functionally weaker participants were shown to perform unloaded (0-kg) and loaded (20-kg) counter-movement jumps more asymmetrically than stronger ones (Bailey et al., 2015). Bailey et al. (2015), however, chose not to relativize task intensity to participant absolute strength, choosing instead to apply the same absolute loads for every participant. Due to the differing relative strength level of the participants, it would follow that the fixed 20-kg loaded jump would be relatively more difficult for the weaker participants. This inter-participant demand variability makes it unclear if this increased asymmetry in the weaker participants was a result of different intrinsic strength levels between groups, or simply a function of relative task difficulty. Our first hypothesis addresses this question, designed to test whether a difference in asymmetry would be seen between exercises which are functionally similar in applied technique but stratified in relative intensity by their vGRF requirements. By finding no significant difference in asymmetry between variations, our study does not support a force-demand based mechanism for vGRF asymmetry in body weight push-ups.

While no population wide asymmetry trends were seen across push-up variations, individualized asymmetry profiles as displayed in Figures 2-6 demonstrate the large degree of variation experienced by participants in both the direction and magnitude of asymmetry across conditions. Figure 1 demonstrates such an example, with the participant force traces in the left column demonstrating a consistent bias towards the right side, whereas the participant in the right column was found to be right side dominant in the TRAD and MAX, while being asymmetrical favoring the left side in the lower intensity MOD. This intra-participant variability has been shown across many different populations, tests and objective measures, with its repercussions for analysis discussed previously in detail (Bishop et al., 2021; Bishop, Turner, et al., 2018; Dos'Santos et al., 2021; T. A. Exell et al., 2012; Virgile & Bishop, 2021). While the intent of investigating different push-up variations was to assess the effect of increasing force demand on force application asymmetry, an anticipated and accepted design risk was that the variation in technique and motor strategy required between these different push-up forms could have a separate intrinsic effect on asymmetry. While the current push-up variations were stratified in terms of task demand, a variety of other differences were subjectively and anecdotally observed. Many of our participants expressed or demonstrated a lack of familiarity with the MOD and MAX conditions. Participants required more assistance from researchers to assume correct starting positioning for the MOD, alluding to a potentially more foreign push-up position. In the MAX, participants required more assistance and direction for correct push-up execution, possibly due to the maximal and explosive nature of the task. These contrasted with the TRAD, with which a relatively higher number of participants seemed familiar, both in starting position assumption and task execution. This disparity in familiarity across participants and the subsequent motor strategy implications speaks to the extent of between-subjects variation during biomechanical analysis.

The second experimental objective was to assess the effect of participant sex as one such between-subject factor, with the hypothesis that female participants would demonstrate significantly higher absolute asymmetry than males. The current study discovered evidence of a sex-based effect, finding female participants to be statistically more asymmetrical than male participants in starting push-up position WtD. Male participant WtD BAI_{ABS} across both positions was 1.8% less than female participants, reaching significance with an effect size of $\eta^2_p = 0.203$. While female WtD BAI_{ABS} changed only negligibly (< 0.25%) from the traditional to the modified starting position, Male participants experienced a 1.5% decrease. For the force-time related variables, only eccentric deceleration phase impulse BAI_{ABS} was significantly different between the sexes ($p = 0.028$, $\eta^2_p = 0.179$), with male participants experiencing 0.75% more asymmetry averaged across variations. As a whole, these findings show a relatively small magnitude trend for female participants, in comparison to males, to have a larger degree of asymmetry in WtD before the start of the push-up, which is then supplanted by a more symmetrical braking impulse during the eccentric phase. This finding is in contrast to countermovement jump research conducted by Bailey et al. (2015) which presented a different trend. Their findings showed that female participants experienced a higher degree of WtD asymmetry in the pre-jump quiet phase than males and performed unweighted countermovement jumps with significantly higher asymmetry in peak force and net impulse. When separated into equal and unequal WtD groups, Sato & Heise (2012) showed that those with unequal WtD while standing were more asymmetrical in total repetition average vGRF during both the 60% and 75% 1RM barbell back squat. Taken together, these results support an opposing trend to the present findings, suggesting unequal WtD as a predictor of increased vGRF asymmetry. It should be noted, however, that these findings relate to lower extremity asymmetry, with the lack of comparable upper-extremity research previously discussed. For power related variables, no significant differences were seen in MAX testing between male and female BAI_{ABS} for mean RFD, eccentric deceleration phase peak RFD and concentric acceleration phase peak RFD. This was echoed by Bailey et al. (2015) who reported no significant differences in RFD between sexes during either loaded or unloaded jumps. They did, however, find peak power asymmetry differences between sexes during the countermovement jump. This lack of significance in power related variables during the MAX could be due in part to a high degree of intra-subject variability in power measures that has been shown to result in poor test-retest reliability (Hogarth et al., 2013; Koch et al., 2012; Parry et al., 2020). These findings are not universal however, with a more recent study investigating push-up asymmetry in a boxing cohort showing better asymmetry results after incorporating a best three repetitions out of five strategy for the MAX repetitions included for analysis (Parry et al., 2021).

Limitations and Future Recommendations

The within and between participant comparisons included in this study allowed for the investigation of sex-based asymmetry differences across three distinct difficulty levels. In terms of face validity, this design appeared appropriate due to the clear difficulty separation between variations, and the reportedly significant force generation differences between groups. Upon review of the data, however, the presence of large intra-individual variation in the magnitude and direction of asymmetry across both task and outcome measure provides further example as to the significant individuality and complexity of asymmetry analysis. While attempts were made to choose variations of push-up with subjectively similar biomechanical profiles, it is possible that the subtle positional and strategy differences between them manifested asymmetry variation which was not exclusively the result of force demand. Additionally, attempts to maximize familiarity (self-selected terminal depth, hand width and pacing), in hopes to capture the most ecologically valid presentation of asymmetry, may have jeopardized the intended clear delineation of variations. Also, this self-selection may have disproportionally benefited those participants who were already familiar with these push-up styles.

Another limitation is the intrinsic simplicity of the assumption that female participants would have differing strength values than male subjects. While this is supported in push-up research, Bailey et al., (2015) demonstrated the value of additional strength testing to better understand the underlying profile of the participants being evaluated. More specificity in group assignment may produce better and ultimately more useful normative asymmetry profiles.

While relatively low asymmetry magnitudes were reported in the current study, it must be remembered that these values represent the average asymmetry, calculated from three trials, before directionality was removed. In this way we are able to capture and convey the magnitude of an overall directional bias of our participants across repeated trials. While this approach may be useful in detecting pushing force imbalances in the aggregate, it does not account for more acute repetition by repetition variation or even more specifically, within repetition variation in asymmetry.

While good reliability of push-up vGRF testing has been shown (Fanning et al., 2021; Hogarth et al., 2013; Koch et al., 2012; Parry et al., 2020, 2021), asymmetry reliability testing in push-ups remains limited. Unaddressed by the current study and within the field, is the effect of form and technique stability, where asymmetry throughout an individual repetitions and across multiple repetitions and trials is assessed. Further analysis may look at the stability of asymmetry and how symmetry changes within and across repetitions and additionally how that degree of stability is related, if at all, to performance and injury risk.

Point to point statistical analysis has been used to this effect during jump testing, with the advantage of incorporating data from throughout the entire repetition instead of discrete phases or instantaneous points (Harry et al., 2021). In this way, practitioners were able to statistically evaluate the extent of asymmetry over the course of a repetition, as well as the direction and magnitude of that asymmetry.

While the current study emphasizes the kinetic asymmetry experienced during push-ups, analyses in the future may be wise to incorporate kinematic analysis in order to determine the root cause of kinetic imbalance during these functional tasks. This approach has been attempted in lower extremity research featuring the back squat, with hip maximum flexion angle asymmetry found alongside increased hip torque asymmetry, while simultaneously showing no ankle kinematic asymmetry in the presence of ankle torque asymmetry (Kobayashi et al., 2010). The difficulties associated with inverse dynamics, notwithstanding, the relationship between asymmetric movement strategies and kinetics remains a vital piece of the story for asymmetry analysis.

Conclusion

To the best of the authors' knowledge this is the first study which attempted to analyze pushing force asymmetry differences between sexes across multiple variations of countermovement push-ups. Results showed that push-up variation, stratified by force demand, did not have a significant effect on pushing force asymmetry in the measures tested. In all, the magnitude of asymmetry experienced by participants was relatively low, with a high degree of variability both within-group and within-participant. This high variability of asymmetry both in the magnitude of side-to-side differences, as well as which limb was higher performing, is consistent with the current literature. While significant differences in asymmetry were found between sexes, these were considered relatively small in both magnitude (< 1.5% BAI_{ABS}) and statistical effect size. Additionally, these differences were limited to only two discrete phases of push-up execution with females more asymmetric in static starting position WtD and males more so in eccentric braking phase impulse. In contrast with previous literature, there was no trend for WtD asymmetry to predict functional asymmetry, speaking further to the high variability and task specificity of asymmetry.

The current findings present a baseline of upper extremity kinetic asymmetry in asymptomatic college aged males and females, providing a starting point for continued research. This growing pool of data, paired with the development and deployment of progressive asymmetry evaluation techniques, will help practitioners better understand and utilize asymmetry analysis as a useful tool in the collective field of exercise science.

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Review of Literature

Introduction

Due to its simple nature and considerable use in both resistance training and rehabilitation, the push-up exercise has been extensively studied by those working in the field of exercise science. While plentiful, the present scope of this research has allowed the exact nature of some core biomechanical characteristics to remain unclear. To date, push-up research has focused primarily on evaluating certain core biomechanical and motor control elements, such as muscular activation patterns (Allen et al., 2013; Cogley et al., 2005; Decker et al., 1999, 2003; Gottschall et al., 2018; Gouvali & Boudolos, 2005; Lear & Gross, 1998; San Juan et al., 2015; Uhl et al., 2003) as well as the kinematic and kinetic variation associated with changing exercise conditions and populations (Dai et al., 2019; Ebben et al., 2011; Hinshaw et al., 2018; Koch et al., 2012; Marcolin et al., 2015; Mier et al., 2014; Moore et al., 2011; Parry et al., 2020, 2021; San Juan et al., 2015; Suprak et al., 2011, 2013; Zalleg et al., 2020). At present, very little research has investigated the potentially asymmetric nature of the push-up exercise, often treating the upper body as a single, bilaterally balanced system (Hinshaw et al., 2018; Hogarth et al., 2013; Parry et al., 2020; R. Wang et al., 2017; Wood et al., 2009). This assumption of balance has led some to disregard one side or the other entirely, either evaluating a participant's dominant limb or another subjectively chosen unilateral side with no accounting for handedness at all. The effect of other variables on the biomechanics of a push-up, such as sex and baseline strength are also understudied, especially as they relate to upper extremity asymmetry. The current review will focus on establishing what is known about the forces and loads involved in push-ups, the relative contribution and importance of the various musculature responsible for creating and controlling these forces, as well as the impact of exercise variance and sex on these measures. Also included, is a review of existing research that has studied the nature of asymmetrical morphology and force production in humans, with an emphasis on the upper extremity where available. Due to the limited quantity of research exploring upper extremity asymmetry, studies which analyzed asymmetry as it pertains to the lower body were additionally included for review.

Push-up Muscular Activation

Muscle activity monitoring during push-up testing, tracked most frequently with electromyography, has helped reveal the relative contributions of different muscle groups during this commonly utilized motor task (Allen et al., 2013; Decker et al., 1999; Gouvali & Boudolos, 2005; Lear & Gross, 1998; San Juan et al., 2015). The primary motor actions of the push-up are the elbow extension and shoulder horizontal adduction components necessary to complete the concentric phase (Allen et al., 2013). Prime movers provide much of the elbow extension and shoulder horizontal adduction forces driving motion, whereas stabilizers, both glenohumeral and scapular, help to maintain correct scapulohumeral alignment through mostly competing eccentric and isometric action (Decker et al., 1999; Lear & Gross, 1998). These muscular forces work together to drive the body up and away from the floor without compromising healthy scapulohumeral rhythm (Lear & Gross, 1998). Different activation patterns have been reported with changing push-up technique. In the case of the modified and traditional techniques, significantly less muscle activity is seen across all muscles measured when moving to an on-knees variation (Gouvali & Boudolos, 2005; San Juan et al., 2015). This specific intensity change is supported further by more general findings from studies with varying methodology, all describing increased muscular activation at the shoulder with increasing load on the arm. (Lear & Gross, 1998; Marcolin et al., 2015; Uhl et al., 2003). Increasing difficulty, either in complexity or load, is thus strongly correlated with increased motor drive at all levels resulting in a higher combined effort from both sides during this motor task.

Prime Movers. Prime movers of the shoulder during a push-up performed in the traditional posture utilizing a shoulder width hand position are the pectoralis major and triceps brachii (Cogley et al., 2005; Marcolin et al., 2015). These muscles drive the shoulder horizontal adduction and elbow extension associated with the concentric phase (Cogley et al., 2005). Relatively narrower hand positions, like those in the traditional and modified styles, specifically increase peak muscular activity of these two muscles during the concentric phase compared to other variations implementing a wider base of support for the hands. (Cogley et al., 2005; Gouvali & Boudolos, 2005; Marcolin et al., 2015). When comparing the relative muscular activation of the pectoralis major and triceps brachii in recreationally trained and healthy males during the traditional and modified variants of a push-up, an overall decrease in the root mean square (RMS) for both muscle groups is seen when moving to the modified, on-knees condition (Gouvali & Boudolos, 2005). For the pectoralis major, the on-knees variant elicited an approximately 15% smaller RMS value for both the left and right sides. For the triceps brachii, RMS values in the modified condition were found to be approximately 5% and 35% less for the right and left side respectively. This finding of decreased motor drive in the modified condition was correlated with additional findings in the same study demonstrating 6% less maximum force relative to body weight required during the completion of a modified pushup when compared to a traditional exercise variant. Furthermore, a lower initial load was seen in the modified starting position. Taken together, these findings suggest a possible relationship between increasing load on the arm and increasing demand on the prime movers to complete the exercise task.

Stabilizers. The serratus anterior is a primary scapular stabilizer and helps to promote stability by upwardly rotating and protracting the scapula in conjunction with humeral movement. (Decker et al., 1999; Lear & Gross, 1998; San Juan et al., 2015) It also helps during the push-up exercise by stabilizing the scapula against the thorax preventing scapular winging. The importance of the serratus anterior is emphasized by its relatively high neural drive during all variations of the push-up (Lear & Gross, 1998; Ludewig et al., 2004). Due to its contributions towards upward rotation and protraction, it can also be considered a primary factor in maintaining proper scapulohumeral rhythm (Decker et al., 1999). Like the prime movers, serratus anterior activation also surges in accordance with increasing task difficulty (Decker et al., 1999; Lear & Gross, 1998; San Juan et al., 2015).

Additional important stabilizers are the upper and lower trapezius muscles which act as stabilizing synergists in conjunction with the serratus anterior to produce the controlled upward rotation which preserves scapulohumeral rhythm (Lear & Gross, 1998). This relationship keeps the glenoid fossa and the humoral head aligned to allow for more healthy joint reaction forces during loaded humoral elevation as is seen in the push-up exercise (Lear & Gross, 1998). The upper and lower trapezius muscles were shown to experience a similar increase in activation when moving to a more difficult push-up variation (Lear & Gross, 1998; San Juan et al., 2015).

The balance of stabilizing muscles is key during a push-up due to the large magnitude of forces experienced. High upper trapezius activation being highlighted as an area of concern due to some push-up variations eliciting upper trapezius activation which may eclipse what the serratus anterior is able to antagonistically match, inhibiting appropriate posterior tilting (Suprak et al., 2013). This concern was prompted by findings during an elevated shoulder angle push-up condition where the degree of posterior tilt was shown to be significantly lower than a traditional position. This finding was unexpected, with previously held notions suggesting that increased arm elevation angle would necessitate increasing scapular tilt during the elevated shoulder push-up (Suprak et al., 2013). When these traditional floor push-up results are compared to scapular kinematic patterns seen during lower intensity wall push-ups with a similar degree of humeral elevation, 15º more posterior tilt is seen (Lunden et al., 2010). It is possible, that increasing task difficulty relative to the shoulder joint, and the subsequent increased muscular demand, may lead to unhealthy scapular compensation limitations as weaker stabilizers are unable to adequately perform. This in turn may allow for unhealthy glenohumeral joint reaction forces and possible opportunities for injury in the shoulder. This was further supported by Ludewig et al. (2004) who, after stratifying push-up variations by level of serratus anterior activation, recommended a push-up progression of wall, kneeling and traditional for those unable to complete the more demanding tasks without provocation of scapular winging or shoulder impingement symptoms.

Push-up Kinetics

Relevant Forces. Measures of vGRFs at the hand during push-up trials reflect the amount of force being generated by the upper extremities to maintain or change the position of the body relative to the floor. Larger vGRFs represent larger forces being applied downward by the body to counteract the force of gravity acting upon it. When comparing the modified and traditional styles of push-up, an increased force output requirement in the traditional technique is required to complete a push-up repetition (Ebben et al., 2011; San Juan et al., 2015; Suprak et al., 2011). This result is based on higher average vGRF, and the greater peak vGRFs found in the traditional compared to the modified push-up through the concentric phases of these techniques. Increasing levels of required relative force may be related to differences, either in subject or condition, which bring the center of mass of the subject forward, closer to the contact point at the hands. These modulations in center of mass position lengthen the relative moment arm which then act on the system, increasing gravitational torque (Ebben et al., 2011; San Juan et al., 2015). When comparing the concentric and eccentric phase of the push-up, the lever arm length increases as one goes into the down position. As the body becomes increasingly parallel to the ground and perpendicular to the line of force for gravity, the required amount of force applied by the hands will have to increase to match. In the modified condition, the lever arm is similarly shortened, having the same general effect.

Body Weight Load. Gouvali & Boudolos (2005) found that the starting position of the modified push-up placed less relative load onto the hands when compared to the traditional push-up at 52.9% and 66.4% percent of total body mass respectively. These findings are supported further by Suprak et al., (2011) and Hinshaw et al. (2018) who found similar body weight loads in the up positions for both push-up variations. In addition to forces applied to the hands, Hinshaw et al. (2018) also measured forces applied to the feet in the starting position showing, predictably, that the feet supported the remainder of the body's weight as the feet and knees are the only other base of support for the traditional and modified variations. By investigating the body weight loads during the range of motion of both push-up variations, Suprak et al. (2011) further demonstrated increasing load as participants moved into the down position, with the traditional technique experiencing an average change from 69% body mass in the up to 75% in the down, compared to 54% and 62% in the modified. Another component of interest is the relative rate at which the demand on the upper extremities changes throughout the range of motion. Findings of Suprak et al. (2011) suggest that exercisers performing the modified version of the pushup experience a sharper rate of upper extremity loading when moving from the up into the down position when compared to the traditional version. This higher rate of loading was expressed as a 15.76% ± 7.03% increase in body weight supported when moving from the up into the down position during the modified technique and a 8.59% ± 3.77% increase for the traditional. These findings highlight the differing loading property dynamics of these two variations which could possibly complicate attempts at direct comparison. One must be mindful of this relationship and consider the effect this sharper modified loading curve might have when compared to the traditional variant.

Force-Time Derived Measures. Peak GRFs are a commonly measured kinetic variable in push-up testing, most often measured and reported as peak vertical GRF (vGRF) or a peak vGRF relative to body weight. Findings relative to these measures reveal significantly higher peak forces in the traditional style compared to the on knees modified condition in healthy college aged subjects (Ebben et al., 2011; Gouvali & Boudolos, 2005). Peak vGRFs were found by Ebben et al. (2011) to be 64%% and 49% of body weight during the traditional and modified on knees position respectively. In another study, peak vGRF was found to be significantly higher in the traditional variant compared to the modified variant when participants were asked to perform the push-up plus modification which requires subsequent protraction of the scapula after the completion of a standard push-up motion (San Juan et al., 2015). In this variation, traditional and modified peak vGRF was found to be 75.99% and 57.95% of bodyweight for each condition respectively. While slightly different in absolute terms of peak force found, the relative difference in experienced forces between the techniques was similar. Like its effect on body weight load, overall task difficulty seems to play a prominent role in the peak force reached when completing these two push-up variations.

During a maximum push-up test in the traditional posture, peak forces for males and females were 129% and 94% of body weight respectively, much higher than the reported values for the standard counter movement push-up seen in other studies (Hinshaw et al., 2018). This trend was also shown in an on-knees maximum variation with peak forces of 107% and 79% of body weight for the male and female participants respectively, but with a similar difference between base of support variations as discussed previously in standard countermovement push-ups (Hinshaw et al., 2018). Peak upper-body power, as well as force at peak power, also demonstrated a similar pattern, both increasing in accordance with task difficulty.

Maximum countermovement push-up results from male college athletes and male boxers were used to study the reliability for force-time derived parameters related to power including peak vGRF, mean vGRF, RFD and impulse (Parry et al., 2020, 2021). For college athletes, moderate to high reliability was seen for peak force, mean vGRF, and impulse (ICC = 0.96–0.98, CV% = 1.7–5.5) with smallest detectable differences of 7.5, 8.6 and 26.1% respectively. RFD was shown to be less reliable (CV = 14.9%; ICC = .87%) (Parry et al., 2020). In elite boxers, substantial to high reliability was seen in all four measures, but with relatively high smallest detectible differences (ICC= 0.80-0.98; CV%= 3-8; 8-33%) (Parry et al., 2021). Researchers utilized a best three repetitions of five methodology with boxers and saw improved RFD reliability compared to the earlier study and in other push-up research which consistently report lower RFD reliability compared to other force-time derived parameters (Hogarth et al., 2013; Koch et al., 2012; Parry et al., 2020). Zalleg et al. (2020) found that vGRF and RFD during the takeoff phase of a maximum counter movement push-up were weakly correlated but significant ($r = 0.48$; $p = 0.001$).

Bilateral Deficit. Synchronous, in-phase bilateral movement styles and force production require a higher instantaneous total body workload and neural drive requirement compared to unilateral or out of phase motor tasks (Aune et al., 2013, 2016). Bilaterally symmetrical maximal contractions of homonymous limbs have been shown to generally produce lower maximal force compared to the aggregate of forces from separate unilateral contractions (Aune et al., 2013). Kuki et al. (2019) showed that collegiate athletes had 36.44% lower totals of peak force during a bilateral isometric mid-thigh pull than the summation of forces during unilateral versions. This relationship implies a total bodily limit for neuromuscular drive, or another limiting bilateral-task specific neurological effect such as increased contralateral, homologous motor inhibition (Aune et al., 2013). The direct causes of these observed bilateral deficits are still largely debated and their relationship with kinetic asymmetry even less understood. If future studies reveal that the total volume of recruited musculature influences the degree of bilateral deficit experienced, then increasing task difficulty could generate a bilateral deficit induced force production limitation. This limitation could then theoretically change the force production outputs of one, or both sides of the body at different rates, potentially affecting the degree of measured asymmetry. Whatever the lever that modulates bilateral deficit, once discovered, further research will be required to understand its relationship to force production asymmetry.

Between-Sex Kinetic Differences. Hinshaw et al. (2018) found that in physically active young adults (21.9 ± 3.5 years) 67% and 64% of body weight was experienced as force applied to the hands at the starting position of the traditional unloaded push-up in male and female participants respectively. In the modified variant, these loads changed to 52% and 48% for males and females (Hinshaw et al., 2018). San Juan et al. (2015) provide insight as to a potential explanation for this difference in their description of moment arm differences between the modified and traditional techniques. The modified technique, with knees on floor, extends the subject center of mass forward relative to the axis of rotation at the feet, increasing the effective moment arm length and increasing gravitational torque. With females having decreased force on the hands in both starting positions, it would follow that they also have a lower baseline center of mass. Mier et al. (2014) describe a shorter effective moment arm seen in female participants due to this difference in distribution of mass compared to males. In contrast to Hinshaw et al. (2018), however, this did not lead to significant differences in relative load between sexes in the up and down positions across the traditional or modified conditions . A possible reason for these different results could lie in study design discrepancies, with push-up lower body base of support positioning described differently across studies. Mier et al. (2014) described the lower body base of support in the modified condition as “lower legs were in contact with the floor with ankles plantar-flexed and back straight”. With feet being plantar-flexed and in contact with the ground, it may be possible that a different lower body center of pressure was established compared to “on knees” positioning in the forementioned studies. It is possible that this positioning extends the effective moment arm towards the feet compared to flexed knee positioning where feet hover above the ground without making contact.

During maximal counter movement push-ups, females were shown to have significantly lower starting vGRFs applied to the hands, as well as lower peak force, peak upper-body power and vGRF at peak power compared to men, all relativized to body weight (Hinshaw et al., 2018). This finding was true for both traditional and modified variants as well as 5% and 10% body weight loaded trials.

Push-up Variations

Due in large part to the easily modifiable nature of the push-up, variations of technique have become ubiquitous in its use and prescription as an exercise task (Harman et al., 2008; Suprak et al., 2011; Wood & Baumgartner, 2004). Deviations in hand orientation as well as in the positioning of the hands and lower body base of support can cause significant changes not only in the relative contributions of the recruited musculature, but in the forces experienced by the upper extremity apparatus as a whole (Cogley et al., 2005). The traditional and modified push-up variations allow for stratification in degree of difficulty due to the changing level of force required to complete the motion (San Juan et al., 2015; Suprak et al., 2013). Push-up modularity thus becomes a useful exercise prescription and programming tool capable of catering directly to a specific level of progression or perhaps targeting a certain tissue for strengthening or rehabilitation purposes (Suprak et al., 2011).

Traditional. The traditional style of push-up is performed with hands placed slightly wider than shoulder width apart and the shoulders themselves placed directly over the hands (Suprak et al., 2011). The feet should then be placed close together and in such a way that that body retains an angle of close to 180 degrees between the shoulders and heels (Suprak et al., 2011). The eccentric phase is defined as the period between the elbows reaching maximal extension and the point of maximal elbow flexion. In the concentric phase, the repetition starts with the end of the eccentric phase and finishes with the return to maximal elbow extension. Often, complete extension in the up phase, and alternatively, elbow flexion past a predetermined reference angle, or depth as measured at a fixed point on the thorax, are markers for the range of motion expected in a standard or modified push-up (Allen et al., 2013). Less precise but more practical measures of acceptable depth, such as the upper arm reaching an angle which is parallel to the ground or the anterior aspect of the chest touching a block of fixed height placed under the sternum, are also often used as markers (Suprak et al., 2011).

Modified. Modified push-ups are similar to traditional in positioning of the upper body but vary in their placement of the lower body base of support (Gouvali & Boudolos, 2005; Suprak et al., 2011). The key difference being that in the modified technique, the knees are in contact with the floor. This change in base of support shortens the effective moment arm while reducing the load placed onto the hands. With decreasing load measured through decreasing vGRF, there becomes a decreased percentage of body weight supported. While the traditional push-up experiences greater absolute load at all points during the range of a push-up, the modified condition experiences a relatively sharper shift in body mass supported when moving from the up into the down position (Suprak et al., 2011). This is likely due to a larger increase in effective moment arm in the modified condition between the up and down position due to the steeper starting angle. This greater degree of transition in moment arm length subsequently causes a greater relative center of mass translation towards the hands thus generating increased loading and a greater rate of vGRF change (San Juan et al., 2015; Suprak et al., 2011).

Maximum. The maximum push-up is most often described as an explosive, single repetition, ballistic countermovement push-up in which the subject is instructed to complete the concentric portion of the push-up as rapidly and powerfully as possible (Hinshaw et al., 2018). Also known as the ballistic push-up, this movement commonly results in the body extending up and away from the floor in such a way as to cause the hands to lose contact with the ground, with maximal trunk flight height set as the subject's outcome goal. This explosive task has proven to be a reliable tool for upper body power assessment, showing a high degree of reliability in force-time derived parameters commonly used to establish strength and power (Hinshaw et al., 2018; Hogarth et al., 2013; Parry et al., 2020, 2021; R. Wang et al., 2017).

Asymmetric Motor Function in Human Movement.

During movement, humans may utilize a wide variety of strategies during the completion of any given motor task. These strategies are comprised of various types and patterns of movement which are combined to form the desired motor action. Broadly, Guiard, (1987) defined bimanual action into four categories as follows: unilateral, bilateral asymmetric, out-of-phase bilateral symmetric, and in-phase bilateral symmetric. Unilateral motions, like throwing a ball, require primary participation of a single limb, whereas bilateral movements with asymmetric motor function, like performing hockey shot, require simultaneous but different upper and lower extremity function. With walking or sprinting, humans use a cyclical, alternating pattern of movement which is asymmetrical moment to moment but require comparatively similar contribution from the right left and right side in total. For in-phase bilateral tasks like jumping and squatting, forces are produced from both sides of the body at similar levels of intensity and at similar points in time in order to apply forces and generate lifting power evenly without jeopardizing balance or risking ineffective completion of the task (Atkins et al., 2016; Kobayashi et al., 2010). While these in-phase bilateral tasks are considered largely symmetrical, and usually visually symmetrical to the naked eye, close examination of the underlying kinematic and kinetic properties of these mirrored movements can begin to reveal differences between sides (Kobayashi et al., 2010). Larger observed kinetic asymmetries during both open and closed kinetic chain tasks have been associated with increased injury risk (Bates et al., 2013; Castanharo et al., 2011; Fort-Vanmeerhaeghe et al., 2020; Paterno et al., 2007; Virgile & Bishop, 2021; H. K. Wang & Cochrane, 2001) as well as deficits in both sport specific and generalized objective performance measures (Bailey et al., 2013; Bell et al., 2014; Bishop et al., 2019; Bishop, Turner, et al., 2018; Sato & Heise, 2012). Laterality is normally assumed to play an important role when these asymmetries are seen, with genetic predispositions, motor control bias and asymmetrical sport participation being commonly assumed factors of change (Aune et al., 2016; Blackburn, 2011; Gutnik et al., 2015). Morphological adaptations in tissues (Bell et al., 2014), and bilaterally disparate neurological coordination (Huster et al., 2011) often described as the underlying causes of these observed side to side force production differences. Subject and task specificity have proven to be important considerations when addressing the direction of asymmetry, with measured dominance and self-reported dominant limb not always congruent (Gutnik et al., 2015; Kuki et al., 2019; Virgile & Bishop, 2021).

Upper Extremity Asymmetry. Absolute percentile difference between upper arm masses in right hand dominant males and females was found to be 5.64% and 3.63%, respectively with a group bias towards the dominant side (Gutnik et al., 2015). While dominant upper arm mass was found to be larger than that of the non-dominant side in both sexes these values did not reach significance. Researchers postulated that this lack of significance could in part be related to an incongruence between participant self-reported dominant upper limb and the side found to be more massive in the study, with 10% of male and 15% of female participants having greater mass in their left upper arm than their right (Gutnik et al., 2015). These dominant limb asymmetry trends were attributed by researchers to the muscular hypertrophy and bone mass development associated with selective movement preferences stemming from bias towards one side of the body (Blackburn, 2011; Gutnik et al., 2015). Blackburn (2011) presented more evidence to this effect, using skeletal samples from English archeological sites to establish a bone mass developmental cross-section of young persons. These findings showed no significant asymmetry in infants and young children with older adolescent children demonstrating a statistically significant right-sided asymmetric bias, lending evidence to a cumulative effect of usage over time. This effect is demonstrated markedly in cases of unilaterally dominant sport where these morphological side to side differences commonly reach significance (Krawczyk et al., 1998). This sport based usage bias would act as a mechanism for the repeated and selective loading of the dominant side which would not only lead to asymmetric soft tissue morphology, but asymmetric bone mass development as well (Blackburn, 2011; Gutnik et al., 2015).

Aune et al., (2016) found that upper extremity bilateral asymmetry was not only greater for the dominant limb in movement and positioning task accuracy, but greater in distal compared to proximal joints as well. For this result, a neurological explanation was proposed: spinal interneurons can have both excitatory and inhibitory effects and can act on contralateral motor neurons. This neural midline crossing has been shown to occur at a significantly reduced rate for distal, compared to proximal muscles. When taken together with findings from Aune et al. (2013), who showed bilateral force deficits to be greater in proximal joints, there is evidence suggesting a proximal to distal, contralateral inhibition effect gradient, with its effects on the asymmetry of force generation remaining unknown. Additionally, Exell et al. (2016) showed that elite gymnasts tend to experience greater kinematic variability in joint position at the shoulder compared to the distal elbow and wrist joints during the touchdown and takeoff phases of a front handspring. They postulated that the presence of vGRF asymmetries, as well as larger kinematic asymmetries at the more proximal joint might be evidence for a possible intra-limb compensatory mechanism which gymnasts might use. While the underlying mechanisms generating these observed asymmetries remain unclear, the baseline presence of asymmetric motor function and morphology is evident.

Upper Extremity Kinetic Asymmetry. In a study including 22 physically active and upper extremity injury free males (age 25.9 ± 1.3 years), researchers found that when performing a clap push-up, the peak vGRF of the subject's preferred limb was significantly higher than the non-preferred limb at 69% and 68% of subject body weight respectively (Koch et al., 2012). Loading rate (calculated as the slope of the force time curve between when vGRF > 50 N and when vGRF = 50 N plus one-third body weight) was also shown to be significantly higher in the preferred limb. No significant difference was seen between limbs for time to peak force. Peak vGRF, as well as all other measures in this study were observed during the eccentric landing portion of these explosive plyometric tasks.

Countermovement push-up kinetics during the eccentric braking and concentric propulsion phase were evaluated in 22 elite male boxers to determine the existence and potential degree of unilateral differences between sides (Parry et al., 2021). No significant difference in any force-time derived parameters (peak force, mean force, flight time, RFD, impulse, and vertical stiffness) were seen between the right and left side pooled group averages of all subjects. This lack of significant differences ($P < 0.001$) was maintained even after dividing subjects into groups organized by boxing style, with conventional (right handed) and southpaw style (left handed) boxers not producing significantly different results when the collected measures for the right sides, and then left sides of each group were compared (Parry et al., 2021). These findings show that even in a population with a substantial training and sport participation induced unilateral usage bias, there can remain a lack of observable kinetic asymmetry during the countermovement push-up. A possible weakness in this study, and in many studies evaluating side to side asymmetry, was the decision to use subjective reporting of preference to organize groups. This choice is likely based on the natural assumption that southpaw boxers would present with left sided bias and vice versa. The findings of Parry et al. (2021) provide important group-based results from a group-based analysis of asymmetry. Although some athletic populations may display more predictable biases, this is not always the case on an athlete-to-athlete basis. Without establishing individualized task specific profiles of limb dominance, a washout effect is possible, where group averages of directional asymmetry are lower than the average absolute asymmetries experienced by participants. This issue can stem from an imperfect understanding of the individualized nature of asymmetry as it pertains to subjective, handedness-based group assignment. A subjectively right-hand dominant subject based on preference and usage, could demonstrate an objectively left-hand dominant profile in whatever metric is being analyzed. Gutnik et al. (2015) demonstrated that 10% of self-reported right-hand dominant subjects were more massive on their "non-dominant" upper extremity limb, and Loffing et al. (2014) found that male college students reported a preference for a southpaw boxing stance 2.4 times more often than a left handed throwing preference. Kuki et al., (2019) originally found no significant difference in peak force or neuromuscular activity during a maximal isometric mid-thigh pull between the self-reported preferred and non-preferred limbs, but after reorganizing limbs by observed peak force dominance, a significant difference was seen between sides, with 5 of the 15 subjects demonstrating higher peak force on their self-reported "non-dominant" limb. These examples further highlight the importance of a decision researchers must make when designing asymmetry studies. One can either choose to seek understandings of pooled group tendencies based on established markers of bias and handedness, such as comparing two classifications of boxers, or throwing vs. non-throwing sides, or alternatively, choose to use absolute asymmetry, described as observed dominance, to establish individualized task and objective measure specific dominance profiles. While you lose the ability to study trends in pre-defined groups, establishing asymmetry at the individual level first, before group assignment, would remove the washout effect of handedness-dominance crossover. It is then possible to discover the average level of absolute asymmetry experienced by a subject pool. While not the stated purpose of Parry et al. (2021), the task specific and individualized nature of asymmetry should be accounted for whenever analyses such as these are performed if the results are to ever be applied in the future assessment of individual subjects or the creation of normative values.

In a study by Fanning et al. (2021), the vGRFs of male collision athletes (gaelic, rugby, soccer, etc.) were assessed during a maximal explosive countermovement pushups. They found similar values between the dominant and non-dominant limb in takeoff and landing peak force, as well as eccentric and concentric phase impulse, all relativized to body weight. For these variables, the standard deviations were quite large, with coefficients of variation ranging from 0.17 to 0.50, implying a large degree of inter-subject variability in kinetic measures. While average group values for the dominant and non-dominant limb were largely similar, the average absolute percentile differences in these different vGRF variables for each individual subject were between 4-11%, with standard deviations of 3-8% and large coefficients of variation. It is possible that these somewhat opposing findings could be due to some subjects producing higher vGRF results on their subjectively non-dominant limb, increasing group statistical variability, and concealing group asymmetry. Also possible, is that large variability in baseline asymmetry profiles amongst individuals within this cohort make group analysis difficult.

Another complication, which extends beyond inter-subject variability, is within-subject, within-limb variability, as discussed by Exell et al. (2012) and later by Dos'Santos et al. (2021). Common asymmetry calculation methods utilize percentages and ratios, usually average values taken from the performances of each limb over a number of trials. The resultant asymmetry index or strength index scores disguise the variability of the underlying discrete values. Unless monitored or reported separately, the loss of this important information may preclude researchers and practitioners from understanding the true asymmetry profiles of their subjects. Exell et al. (2012) recommends asymmetry findings only be considered meaningful when they eclipse the level of intra-limb variability observed with coefficient of variation calculations used as a cutoff.

Peak force asymmetry was evaluated in U.S. Marines with and without injury during a maximum push-up from a bent elbow position (Poploski et al., 2020). In healthy controls, maximum force relative to body weight was 6.20 ± 0.68 N/kg and 6.12 ± 0.68 N/kg for the dominant and non-dominant sides respectfully. These values were found to be significantly different (P=0.037). In injured subjects, only those with injuries to their non-dominant limb were found to have significantly different peak forces, at 6.47 ± 0.43 N/kg and 6.22 ± 0.45 N/kg for the dominant, uninjured upper extremity and the injured, non-dominant extremity respectively (P=0.001). These findings suggest a pattern of asymmetry with the significant dominant side asymmetry in peak force observed in healthy controls giving way to a lack of significant asymmetry in those with dominant side injury. Marines with non-dominant side injury then experiencing the largest reported asymmetry. Taken together, these findings provide evidence for a generalized bias towards the dominant side that is possibly persistent even through injury, with those having dominant side injuries appearing objectively balanced. Researchers caution that symmetry after injury, without consideration of pre-injury function, should not be viewed as a marker of readiness to resume normal activity (Poploski et al., 2020).

Dai et al. (2019) analyzed the ballistic countermovement push-up peak force asymmetry of 304 male and 195 female NCAA Division I athletes from 14 different sports. They found asymmetry values for the male participants between 11% and -6% for athletes within the 90th and 10th percentiles for asymmetry, with positive numbers associated to self-selected dominant side bias. Average asymmetry for all male athletes was 2 ± 7%. 90th and 10th percentile asymmetry cutoffs were 9% and -7% for females with a total group average asymmetry of 1 ± 7%. Thus, strength asymmetry was reported by Dai et al. (2019) to generally fall below 10% for athletes based on these findings. This was later used as additional support for an arbitrary 10%

asymmetry cutoff widely recommended in the literature for use in return to sport decision making by clinicians. When incorporating the earlier criticism of Parry et al. (2021), and the findings of Fanning et al. (2021), this claim of support for the 10% cutoff as a metric for evaluation of individual athletes is potentially unfounded. With such low average asymmetries and such high standard deviations a similar washout effect due to sorting groups by handedness is possible akin to what was seen in other studies. Dai et al. (2019) specifically address the importance of an individualized approach to asymmetry due to the variable asymmetry profiles seen in athletes from different sporting backgrounds. Asymmetry index, calculated using the side with the observed dominance as the reference limb, reduces the likelihood of asymmetry washout by more objectively classifying limbs on an individual subject, task and objective measure specific basis. If reference values and normative data are collected and presented in this way, then when assessing an individual athlete or patient, practitioners can then look at the objective absolute asymmetry they observe without needing to utilize a subjectively chosen reference limb. The downfall of this method, however, is that baseline assessments of patients and injured athletes must be completed before injury to have the best idea of how far from baseline their injury has taken them, in order to know what their goals and targeted symmetry profile will be during rehabilitation. Without that, interpretation of post-injury asymmetry becomes more clouded.

If the goal of studying asymmetry in healthy populations is to create normative values that are generalizable and allow for future determinations of strength deficits in an individual patient or athlete, then the individualized nature of asymmetry must be considered and accounted for in study design and the reporting of findings. Studies broaching this topic need to address all factors and be mindful of how task and objective measure specific asymmetry can be. This includes accounting for variability at all levels including the lesser discussed within-limb variability (Dos'Santos et al., 2021; T. A. Exell et al., 2012; Virgile & Bishop, 2021).

Lower Extremity Asymmetry. Although the upper extremity has been researched extensively in regard to morphological asymmetry and motor control (Aune et al., 2016; Blackburn, 2011; Gutnik et al., 2015; Huster et al., 2011), upper extremity force production asymmetry and how it pertains to sport and performance remains relatively understudied, especially as it pertains to the push-up task (Fanning et al., 2021; Parry et al., 2020). When deciding how best to investigate the topic of upper body kinetic asymmetry, consideration can be given to other areas of research to help formulate study design and delineate potential avenues of study. Lower extremity motor function has been extensively researched for asymmetric biomechanical markers during tasks related to sport and performance. To gather additional important background from the body of biomechanics research available, analysis of studies focusing on bilateral lower body tasks are included for review.

Lower Extremity Kinetic Asymmetry. When analyzing the kinetic profiles of healthy subjects during bilateral tasks such as squatting, jumping and the bilateral isometric mid-thigh pull, a preponderance of the pertinent research reports a general trend for a small degree of group asymmetry (ASI < 10%) favoring the self-reported dominant limb (Atkins et al., 2016; Bailey et al., 2013, 2015; Sato & Heise, 2012) or the right side (Bell et al., 2014). These studies, with subjects ranging from highly trained athletes in various sports to recreationally trained individuals, all display group averages of relatively similar magnitude and direction of asymmetry in kinetic parameters like peak vGRF, phase specific impulse and peak torque (Bailey et al., 2015; Bell et al., 2014; Kobayashi et al., 2010; Kuki et al., 2019; Schons et al., 2019). This trend is even seen in more field-oriented measures, like the functional movement screen (Atkins et al., 2016). In contrast, some researchers show disparate findings. While Bishop et al. (2020) reported a similar magnitude of absolute asymmetry in the force-time derived measures of female soccer players during the unilateral squat and countermovement jump (~6-17%), their findings differed in that a trend for dominance was present favoring the non-dominant, non-kicking support leg. Researchers postulated a possible sport specific bias for non-dominant limb support and weight bearing task dominance in soccer players due to the repeated single leg loading experienced by the non-kicking support leg. Significance was not reached for this directionality of asymmetry in part because of the substantial degree of variability between subjects and between tests, with only fair to moderate levels of agreement in the direction of asymmetry between the squat and countermovement tests for jump height, peak force and concentric phase impulse (Kappa = 0.35 – 0.45). Only peak power was shown to have a substantial level of agreement (Kappa = 0.61). It is important to remember, however, that it is unknown to what extent the bilateral vs. unilateral nature of a task affects the magnitude and directionality of asymmetry and one must be mindful of the extent to which these different approaches are compared.

Kuki et al. (2019) showed that male collegiate athletes demonstrated absolute peak force asymmetry values of 23.28 ± 14.37% and 10.26 ± 8.09% for the bilateral and unilateral maximal isometric mid-thigh pull. Also shown, was that in the bilateral isometric mid-thigh pull, a significant difference in the neuromuscular activity of the vastus lateralis was seen between limbs, with the force generation determined dominant limb being greater (71.03 ± 22.33%; 53.54 ± 14.85%; $p < 0.05$, $d = 0.92$). The need for objectively determined limb group assignment is highlighted in this study with five (bilateral IMTP) and seven (unilateral IMTP) of the fifteen subjects self-reporting preference in a leg which would later be determined to be less dominant in terms of observed peak force. Due to the significant difference in vastus lateralis activation during the bilateral IMTP and the significant difference in strength imbalance between the unilateral and bilateral peak forces, researchers discussed the possibility of a subconscious selection mechanism, potentially allowing subjects to compensate for their non-dominant leg during bilateral tasks. This provides a possible explanation as to why there was greater imbalance for the bilateral tasks because subjects were forced to utilize each leg individually during the unilateral test. This possibly reveals another contributing factor beyond absolute strength asymmetry, with the inclusion of subconscious preference and utilization modulating observed forces. Another theory discussed is that inter-hemispheric inhibition may have played a role, with inhibition of the motor cortex controlling the non-dominant side leading to both lower activation of the vastus lateralis and the resulting lower peak force (Kuki et al., 2019). These findings and these possible explanations further working theories of how bilateral deficit and asymmetry may be related.

Bell et al. (2014) performed a regression-based analysis to study the impact of lean mass asymmetry on the kinetic asymmetry experienced by student athletes during a counter-movement jump. They found that asymmetry in the thigh and shank explained 20% of the variance in peak force ($R^2 = .20$, $P < 0.001$), while the thigh, shank and pelvis combined to explain 25% ($R^2 = .25$, $P < 0.001$). While average asymmetry was found to be quite low among subjects for all measures (1-3%), the range of absolute asymmetry measured among subjects was quite large (0-25%). Normative value establishment was a secondary purpose of this study, demonstrating peak force asymmetry values of 16.79% and -11.79% for the 97.5th and 2.5th percentiles of the population respectively (positive and negative values reflect strength asymmetry towards the dominant and non-dominant side respectively). When compared to commonly utilized, but so far arbitrarily designated thresholds for healthy asymmetry limits and rehabilitation targets of 10% asymmetry, 20%, and 6% of healthy student-athletes fell outside of this range for peak force and peak power. Only 3 and 7 out of 167 subjects were shown to elicit asymmetry above 15% for peak force and peak power, potentially establishing a better “high risk” asymmetry cutoff (Bell et al., 2014). These findings compare favorably to Impellizzeri et al. (2007) who found peak force asymmetry values in the squat jump for the 97.5th and 2.5th percentile to be 15.0% and -15.1% respectively.

In a study by Bailey et al. (2015) which looked at force production asymmetry in athletes of differing strength values, those considered to be less functionally strong preformed jumping tasks with more asymmetry than those of the stronger group. This coincides with the results of Bell et al. (2014) who showed that a greater that 10% asymmetry in peak power resulted in a 3.5 inch decrease in countermovement jump height. Researchers attributed these differences to a potential relationship with absolute strength. This may be related to a description used by Jaszczak, (2008) to explain why alternating movements seem to elicit less asymmetry than mirrored movements. The postulation was that limitations of neural drive, due to the relative whole body and bilateral nature of a given task, could limit force generation capacity. This decreased force output potential could then lead to a preference for more asymmetrical strategies to overcome limitations established by insufficient neural drive and the resulting decrease in force output. Schons et al. (2019), however, did not show a significant relationship with jump height and isokinetic peak knee extensor torque asymmetries (11.24 ± 5.33 at 60 deg/s, 5.28 ± 3.26 at 180 deg/s and 8.35 ± 5.26 at 300 deg/s).

While functional jump tests and lab based isometric and isokinetic testing are the most frequently used methods to assess interlimb strength asymmetry, squat-based tests have also been used. After separating groups based on baseline standing weight distribution, results showed that the more asymmetrical group in standing weight distribution performed the 60% and 75% 1RM back squat with significantly higher average vGRF asymmetry and with more rotational and angular bar displacement. All asymmetry values in this study were less than 5% towards the stronger side (Sato & Heise, 2012). Boys, grouped by ages ranging from 12 to 16, showed significant right sided deep squat peak vGRF asymmetry ranging from 4-13% with the occurrence of a left sided kicking preferences in these ages between 7 and 26%. Kobayashi et al. (2010) showed no significant vGRF asymmetry in the back squat at 50, 70, and 90% of 3RM in long jumpers, but showed increased inverse-dynamic calculated hip torque asymmetry favoring the takeoff leg. The decoupling of torque and vGRFs raises questions as to the kinematic variability of a task which is subjectively symmetrical. Gymnasts also displayed proximal joint force asymmetry, but in that instance it was paired with an observed pattern of kinematic variability in the front handspring (Exell et al., 2016). Kinematic variability, and the varied proportion of force generation each joint produces, may explain some observed kinetic asymmetry. Therefore, kinematic asymmetry should be carefully controlled or monitored to ensure that it does not introduce uncontrolled variability into data collection.

Upper Extremity Sport Specific Asymmetry. Upper extremity vGRFs of six national-level gymnasts were evaluated during the hand contact phase of a front handspring in order to detect the presence of kinetic asymmetry (Exell et al., 2016). These contact phase forces are grossly like those experienced in a push-up and were described by researchers as absorbing and stabilizing periods during the completion of the task. Researchers found that three of the six subjects experienced statistically significant asymmetry in maximum vGRF and that there was a general trend of asymmetry towards the side corresponding to the leading leg. As was hypothesized by the researchers, asymmetry levels found in this study suggest an athlete specific profile of asymmetry that is influenced by the motor strategies utilized. This was confirmed by the kinematic data, which showed that four of the six athletes demonstrated significant differences in four or more of the eight kinematic measures. Based on the findings that no two gymnasts in this study demonstrated a similar pattern of kinematic and kinetic asymmetry, researchers recommended an individualized, athlete specific approach to asymmetry.

While the existence of functional and dynamical asymmetry may be expected in sports which utilize a high degree of unilateral movements such as basketball, volleyball, and soccer (Marinsek, 2016), in swimming, asymmetrical movement patterns are commonly considered to be detrimental to performance (Jaszczak & Zatoń, 2011). When 18 locally competitive male swimmers were evaluated for peak force and RFD asymmetry during the front crawl swimming technique, researchers found that symmetry indices for these two measures were 11% and 13% respectively with force output being higher in the stronger of the two arms (dos Santos et al., 2017). Strength dominance in this study being determined by the inclusion of a land based isometric swimming specific strength test which found 14% and 17% symmetry indices in peak force and RFD respectively (dos Santos et al., 2017). Values of asymmetries in this alternating motor task cannot, however, offer complete and clear insight into the question of asymmetry during mirrored tasks. These bilateral tasks may differ in how they are affected by factors such as neural drive capacity limitations, and other mirrored movement specific differences. Due to the infrequent use of bilaterally symmetrical upper extremity motor strategies in human movement there are only a few obvious targets for research on asymmetry during tasks which are functionally mirrored similar to that of a push-up. The breaststroke swimming technique presents an opportunity to evaluate forces from a bilateral task which by all obvious subjective measures requires relatively symmetrical force production to perform successfully. In a study utilizing a swimming ergometer to evaluate the upper extremity forces of male and female college age students, researchers found the bilateral breaststroke technique to be more symmetrical than the alternating strategy of the front crawl for both males and females (Jaszczak, 2008). This was found to be the case both before and after adjusting for relative maximum forces, with significance being reached for the female group ($p=0.000$, $p=0.000$) in both cases and approaching significance for the males in both raw dynamical asymmetry and relative asymmetry respectively ($p=0.063$, $p=0.060$). These findings of asymmetry during the performance of the mirrored breaststroke technique were corroborated by a similar study which found adolescent boys to have similar asymmetry when performing the breaststroke, with absolute percentile asymmetry values of nearly 25% (Jaszczak & Zatoń, 2011). This study, like the previous one, did not report on handedness or left right bias in their calculations, instead looking at the absolute value of asymmetry in their subjects independent of direction.

Sport climbers have been observed to preferentially utilize their dominant limb, with a significantly different load application percentile on the right and left hand at 53 ± 3.8% and 47 ± 3.8% respectively ($p < 0.001$) (Donath et al., 2013). This degree of asymmetric usage was found to increase after a fatiguing protocol, significantly decreasing the load application percentage on the left hand while simultaneously increasing load application on the right (Donath et al., 2013). Advanced climbers, however, seem to utilize less of this asymmetrical preference, with significantly more left (non-dominant) hand incorporation when climbing ($p < 0.05$). In addition, advanced climbers showed no significant difference in break time, measured as a percentage of the total load application time ($p > 0.05$), whereas recreational climber break time was found to be largely different, with a bias for the non-dominant hand to receive more relief ($p < 0001$). These findings suggest that experience and fatigue both play an important role in the cumulative workload symmetry of a task, with fatigued and less experienced participants favoring their dominant limb more. While the relationship is not explicitly shown, this evidence supports the notion that climbing experience and the requisite cumulative training effect it has on the athlete produces a more fatigue resistant non-dominant side and subsequently more balanced upper extremity utilization. This likely correlation adds evidence for a training effect, either by way of technique, or through muscular training adaptation, for increasing symmetry with increasing sport specific skill or adaptation. These findings then detract from the theory of selective use and limb dominance being a training adaptation and potentially establishes the opposite (Donath et al., 2013).

Unilaterally favored sports, such as volleyball and tennis, create numerous examples of asymmetric muscular imbalance and movements most likely caused in their more extreme forms by a sport related bias (Krawczyk et al., 1998; H. K. Wang & Cochrane, 2001). These extreme findings however, are in contrast with other findings that saw no correlation between asymmetry and the particular sport that athlete participated in, again supporting a more individualized approach to asymmetry (Dai et al., 2019).

Between-Sex Asymmetry Differences. Females have been found to have significantly less asymmetry than males in self-reported dominant side upper extremity limb mass compared to the non-dominant side (Gutnik et al., 2015). Possible explanations attribute this difference to disparate motor control behavior between sexes due to neurological differences in the brain (Gutnik et al., 2015; Huster et al., 2011). These morphological differences have been associated with increased functional lateralization in males due to a possibly larger degree of hemispheric dominance favoring the left side of the brain (Huster et al., 2011). Left- and right-hand dominant females were shown to lack asymmetry in upper extremity, contralateral joint movement velocity reproduction accuracy (Adamo et al., 2012). Conversely, male participants were shown to be significantly asymmetrical, with a velocity matching accuracy bias to the participants dominant limb for both left- and right-hand dominant participants. This lateralization trend for males shown in these motor control studies is possibly a contributing factor towards increased asymmetrical musculoskeletal mass accumulation as shown in morphological studies, perhaps through repetitive asymmetric tendencies over time. Extrapolated further, this asymmetry in musculoskeletal mass, and potential force generating tissue, could predispose males to increased force production asymmetry potential in maximal use cases.

This theoretical relationship, however, is weakened by the findings of Bailey et al., (2015) which found that females tend to produce force in maximal jumping tasks more asymmetrically than males. In both the squat jump and countermovement jump, average absolute peak force asymmetry was found to be higher for the female group compared to the male group with asymmetry index scores of 3.78 ± 0.06 % and 1.95 ± 0.02 % (Cohen d= 0.64) in the unweighted squat jump and 6.89 ± 0.08% and 4.65 ± 0.09% (Cohen d= 0.51) in the unweighted countermovement jump for females and males respectively. Females were also shown to produce forces during a standing weight distribution trial more asymmetrically as well (p= .003, Cohen d = 0.82). While the subjects of this study were homogenous in that they were all Division 1 college athletes, researchers did consider the sport specific participation of the athletes included, noting that 5 of the 7 female athletes with especially high weight distribution asymmetries were soccer players. Bishop et al. (2020) reported much the same, showing a trend for non-dominant lower extremity bias in single and bilateral jumping forces in female soccer players. Sport specific biases may play a role in the development of force production asymmetries and until those relationships are better understood the true homogeneity of groups studied should be carefully considered. In contrast, Fort-Vanmeerhaeghe et al. (2020) found no significant difference in the asymmetry index scores of male and female athletes in either the single leg counter-movement jump and single leg hop test. Additionally, Bell et al. (2014) found no significant influence of sex on their regression models for lower body lean mass asymmetry in regards to predictions of peak force and power asymmetry. Males and females were also reported to have similar maximal force asymmetry during the breast stroke and front crawl swimming techniques (Jaszczak, 2008).

Summary

While the push-up exercise enjoys widespread use as a strength training, rehabilitation and performance evaluation tool, its profile in regard to kinetic asymmetry remains unclear. The presence of asymmetry in human movement has been shown to range broadly, in both type and intensity. Morphological, neurological, kinematic, and kinetic asymmetry have all been demonstrated in a wide range of populations, while performing a variety of different tasks, across many objective measures. The lack of conclusive and consistent findings regarding the magnitude and direction of kinetic asymmetry across subject groups and performance tasks has lent to recommendations that future research take the high variability and individualized nature of asymmetry into account. While so far limited, further push-up asymmetry investigation may have performance implications as well as injury prevention and rehabilitation applications proportional to the push-ups already substantial use in those fields. As a result, the goal of this proposed study is to evaluate the presence of bilateral vGRF asymmetries in healthy college aged males and females during several variations of a push-up. By leaning on the recommendations for studying asymmetry produced from earlier research, this study will account for the individualized nature of asymmetry as well as the task and objective measure derived variability demonstrated previously. In doing so, kinetic asymmetry analysis, comparing college age male and female participants across both maximal and sub-maximal variations of push-up will produce novel normative values for use in future research, training, and rehabilitation.

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Appendix A: Journal of Sports Sciences Submission Guidelines

Journal of Sports Sciences

Instructions for authors:

https://www.tandfonline.com/action/authorSubmission?show=instructions&journalCode=rjsp20

Appendix B: Custom MATLAB script

```
clc
clear;
```

Multiple subject analysis

```
% Automaticially runs analysis for all subjects in a folder in numerical order starting
% with S1, requires there to be no gaps in subject, condition or trial data
% files.
```

Setup folders and trials

Before starting, create a parent folder to contain your individual subject folders. Then create a child folder called 'Data Summaries' which will be where a second copy of the output .csv file will be stored after first being stored within the individual subject folder.

```
% Trial naming convention for automation is as follows:
% S1_C1_T1 ... S25_C3_T3
```

gather information from user

```
prompt = {'Enter Subject count:'};
dlg_title = 'Subject count';
answer=inputdlg(prompt, dlg_title);
SubjectCount=answer(1);
SubjectCount=str2double(SubjectCount);

prompt='Select parent folder containing subject folders ';
[path]=uigetdir(path,prompt);

for subject=1:SubjectCount
Subjectnumber=num2str(subject);
SubjectID=strcat('S',Subjectnumber);

% Automated opening of standing trial
subpath=strcat(path,'/',SubjectID,'/');
SubjectIDFileTag=strcat(SubjectID,'_');
SubjectIDFileTag=char(SubjectIDFileTag);
CondFileTag='C0_';
TrialFileTag='T1';
SWfile=strcat(SubjectIDFileTag,CondFileTag,TrialFileTag,'.c3d');
SWfile=char(SWfile);
[Markers,VideoFrameRate,AnalogSignals,AnalogFrameRate,Event,ParameterGroup]=readC3D([subpath
SWfile]);
```

Standing trial raw C3D proccessing

```
SWFzLeft=-(AnalogSignals(:,3)); SWFzRight=-(AnalogSignals(:,9));
SWLeft = mean(SWFzLeft);
SWRight = mean(SWFzRight);
SWTotal = SWLeft+SWRight;

TimeInc=1/VideoFrameRate;
%Calculate standing weight AI
SWSize=size (SWFzLeft);
SWAI=((SWRight-SWLeft)/SWTotal)*100;
```

Initialize arrays to be populated

```
TradConImpRightArray = []';
```

```
TradConImpLeftArray = []';
TradConImpAIArray = []';
ModConImpRightArray = []';
ModConImpLeftArray = []';
ModConImpAIArray = []';
TradEccImpRightArray = []';
TradEccImpLeftArray = []';
TradEccImpAIArray = []';
ModEccImpRightArray = []';
ModEccImpLeftArray = []';
ModEccImpAIArray = []';
TradPeakFzRightArray = []';
TradPeakFzLeftArray = []';
TradPeakFzAIArray = []';
TradTotalPeakFzArray =[]';
ModPeakFzRightArray = []';
ModPeakFzLeftArray = []';
ModPeakFzAIArray = []';
ModTotalPeakFzArray = []';
TradTTPRightArray = []';
ModTTPRightArray = []';
TradTTPLeftArray = []';
ModTTPLeftArray = []';
TradEccDecImpRightArray = []';
TradEccDecImpLeftArray = []';
TradEccDecImpAIArray = []';
TradTotalEccDecImpArray = []';
ModEccDecImpRightArray = []';
ModEccDecImpLeftArray = []';
ModEccDecImpAIArray = []';
ModTotalEccDecImpArray = []';
TradConAccImpRightArray = []';
TradConAccImpLeftArray = []';
TradConAccImpAIArray = []';
TradTotalConAccImpArray = [];
ModConAccImpRightArray = []';
ModConAccImpLeftArray = []';
ModConAccImpAIArray = []';
ModTotalConAccImpArray =[];
TradBWSuppRightArray = []';
TradBWSuppLeftArray = []';
TradBWSuppAIArray = []';
TradTotalBWSuppArray=[]';
ModBWSuppRightArray = []';
ModBWSuppLeftArray = []';
ModBWSuppAIArray = []';
ModTotalBWSuppArray=[]';


for j=1:6
```

Analyze each push-up file

```
 %Create trial name to prompt user to open
    %Establish the condition name
    if j<4
        CondTag='Trad';
    else
        CondTag='Mod';
    end
%
%Establish the trial number to open
```

```
if j==1||j==4
    TrialTag='01';
elseif j==2||j==5
    TrialTag='02';
elseif j==3||j==6
    TrialTag='03';
end
```

Open Condition 1 and Condition 2 Push-up Kinetics file

3 reps, no lift off, continuous.

```
% Automated opening of condition 1 and condition 2 trials
SubjectIDFileTag=strcat(SubjectID,'_');

if j<4
        CondFileTag='C1_';
    else
        CondFileTag='C2_';
end

if j==1||j==4
    TrialFileTag='T1';
elseif j==2||j==5
    TrialFileTag='T2';
elseif j==3||j==6
    TrialFileTag='T3';
end

PUfile=strcat(SubjectIDFileTag,CondFileTag,TrialFileTag,'.c3d');
PUfile=char(PUfile);
[Markers,VideoFrameRate,AnalogSignals,AnalogFrameRate,Event,ParameterGroup]=readC3D([subpath
PUfile]);

FzLeft=-(AnalogSignals(:,3)); FzRight=-(AnalogSignals(:,9));
C7=Markers(:,1,3);C7_vert=C7/1000; %Put data into arrays
FzLeft_downsample = downsample(FzLeft, 10);
FzRight_downsample = downsample(FzRight, 10);

%Downsample force and unit correct kinematics
FzTotal=FzLeft_downsample+FzRight_downsample; % Added by TW
C7_vert = C7_vert/1000;  %Convert each element from mm to m
```

Calculate initial weight supported and AI

```
BWPoints=100;

%Calculate Force supported by each side over the first bit of the trial, before movement
BWSuppLeft=mean(FzLeft_downsample(1:BWPoints));
BWSuppRight=mean(FzRight_downsample(1:BWPoints));
BWSuppTot=BWSuppRight+BWSuppLeft;
EccThreshold=BWSuppTot-(.05*BWSuppTot);
RelativeBWSuppTotal=BWSuppTot/SWTotal;
%Calculate BWSupported AI
BWSuppTot=BWSuppRight+BWSuppLeft;
BWSuppAI=((BWSuppRight-BWSuppLeft)/BWSuppTot)*100;
if j<4
    TradBWSuppRightArray=[TradBWSuppRightArray BWSuppRight(1)];
    TradBWSuppLeftArray=[TradBWSuppLeftArray BWSuppLeft(1)];
    TradBWSuppAIArray=[TradBWSuppAIArray BWSuppAI];
    TradTotalBWSuppArray=[TradTotalBWSuppArray RelativeBWSuppTotal];
else
    ModBWSuppRightArray=[ModBWSuppRightArray BWSuppRight(1)];
```

```
    ModBWSuppLeftArray=[ModBWSuppLeftArray BWSuppLeft(1)];
    ModBWSuppAIArray=[ModBWSuppAIArray BWSuppAI];
    ModTotalBWSuppArray=[ModTotalBWSuppArray RelativeBWSuppTotal];
end
```

Deliniate phases of interest

```
% Option 1 using %BW change to find start of the eccentric phase, when force deviates from weight
% Added by TW

% PUFzTotBegMean=mean(FzTotal(1:100));
% ECCThreshold=PUFzTotBegMean-(.025*PUFzTotBegMean); %(Barker et al., 2018)

%Option 2 using C7 to find start of the eccentric phase, when C7 height deviates from baseline C7
height
% Added by TW

PUC7AvgStartingHt=mean(C7_vert(1:100));
ECCThreshold=PUC7AvgStartingHt-(.20*PUC7AvgStartingHt); % 20% drop below baseline C7 average
height is aggressive in order to remain robust agaist C7 noise during the pre-phase. Does not
return a biomechanically accurate start to the eccentric phase.

TempStartIdArray=[];
TempStartIdArraySize=size(TempStartIdArray);

s = 50;
while TempStartIdArraySize<15
    if C7_vert(s)<ECCThreshold
        TempStartIdArray(s)=s;
    else
        TempStartIdArray=[];
    end
    s=s+1;
    TempStartIdArraySize=size(TempStartIdArray);
end

CMStartId=s-15;
```

Establish the middle rep

```
%Find the BEGINNING of the first concentric phase (bottom of C7 trajectory)
TempEccArray = [];
i=CMStartId; % Used to begin after a significant portion of the first rep eccentric phase has
passed. % Edited by TW
TempEccArraySize = size (TempEccArray);

while TempEccArraySize <25
    if i>VideoFrameRate
        if C7_vert(i)<C7_vert(i+1)
            TempEccArray=[TempEccArray i];
        else
            TempEccArray=[];
        end
    end
    TempEccArraySize=size(TempEccArray);
    i = i+1;
end
FirstTrough = TempEccArray(1);


%Find the END of the first concentric phase (top of C7 trajectory) and
%beginning of second eccentric phase (second rep)
```

```
TempConArray = [];
i=FirstTrough;
TempConArraySize = size (TempConArray);
while TempConArraySize <30
    if C7_vert(i) > C7_vert(i+1)
        TempConArray = [TempConArray i];
    else
        TempConArray = [];
    end
    TempConArraySize = size (TempConArray);
    i = i+1;
end
FirstPeak = TempConArray(1);

%Find the END of the second eccentric phase (bottom of C7 trajectory)and
%beginning of second concentric phase
TempEccArray = [];
i=FirstPeak;
TempEccArraySize = size (TempEccArray);
while TempEccArraySize <25
    if C7_vert(i) < C7_vert(i+1)
        TempEccArray = [TempEccArray i];
    else
        TempEccArray = [];
    end
    TempEccArraySize = size (TempEccArray);
    i = i+1;
end
SecondTrough = TempEccArray(1);

%Find the END of the second concentric phase (top of C7 trajectory)
TempConArray = [];
i=SecondTrough;
TempConArraySize = size (TempConArray);
while TempConArraySize <25
    if C7_vert(i) > C7_vert(i+1)
        TempConArray = [TempConArray i];
    else
        TempConArray = [];
    end
    TempConArraySize = size (TempConArray);
    i = i+1;
end
SecondPeak = TempConArray(1);

%Create time series for kinematics
TimeSeries = [];
C7_vert_size=size(C7_vert);
for k=1:C7_vert_size
    if k==1
        TimeSeries (k) = 0;
    else
        TimeSeries (k) = (k-1)*(1/VideoFrameRate);
    end
end
TimeSeries = TimeSeries';

%Create time series for kinematics
TimeSeriesRep = [];
timeseries_size=size(TimeSeries);
for k=1:timeseries_size
    if k==1
```

```
        TimeSeriesRep (k) = 0;
    else
        TimeSeriesRep (k) = (k-1)*(1/VideoFrameRate);
    end
end
TimeSeriesRep = TimeSeriesRep';

%Define boundaries of second rep
C7VertRep=C7_vert(FirstPeak:SecondPeak);
FzLeftRep=FzLeft_downsample(FirstPeak:SecondPeak);
FzRightRep=FzRight_downsample(FirstPeak:SecondPeak);
TimeSeriesRep=TimeSeries(FirstPeak:SecondPeak);
```

Plot condition 1 and condition 2 C7 data

```
% figure;
% plot(TimeSeries, C7_vert);
% title(strcat(SubjectID,CondTag,TrialTag)) % Added by TW
% ylabel ('C7 Vertical Marker Position (m)') % designate label of the left y-axis
% xlabel ('Time (s)')
% hold on
%
%  %Plot start of middle eccentric phase
%  plot(TimeSeries (FirstPeak) ,C7_vert(FirstPeak), 'ko');
%  hold on;
%
%  %Plot end of middle eccentric phase, start of middle concentric phase
%  plot(TimeSeries (SecondTrough) ,C7_vert(SecondTrough), 'ko');
%  hold on;
%
%  %Plot end of middle concentric phase
%  plot(TimeSeries (SecondPeak) ,C7_vert(SecondPeak), 'ko');
%  hold on;
```

Plot force traces with C7 displacement

```
%Plot data to check
figure;
title(strcat(SubjectID,CondTag,TrialTag))  % Added by TW

yyaxis left;
plot(TimeSeriesRep, FzLeftRep);
hold on;
plot(TimeSeriesRep, FzRightRep);
hold on;


yyaxis right;
plot(TimeSeriesRep, C7VertRep);
ylabel ('C7 Vertical Marker Position (m)') % designate label of the left y-axis
xlabel ('Time (s)')
hold on;

legend('GRF Left','GRF Right','C7 Position','Location','southeast'); % designate the plot legend
text and location


 %Get Fz for the eccentric phase of the middle rep
 FzLeftEcc = FzLeft_downsample (FirstPeak:SecondTrough);
 FzRightEcc = FzRight_downsample (FirstPeak:SecondTrough);

 %Get Fz for the concentric phase of the middle rep
```

```
  FzLeftCon = FzLeft_downsample (SecondTrough:SecondPeak);
  FzRightCon = FzRight_downsample (SecondTrough:SecondPeak);

  %Calculate impulse and AI for full concentric portion
  ConTime=(size(FzRightCon))*TimeInc;
  ConImpLeft=(mean(FzLeftCon))*ConTime;
  ConImpRight=(mean(FzRightCon))*ConTime;
  ConImpComb=ConImpLeft+ConImpRight;
  ConImpAI=((ConImpRight-ConImpLeft)/ConImpComb)*100;

  if j<4
      TradConImpRightArray=[TradConImpRightArray ConImpRight(1)];
      TradConImpLeftArray=[TradConImpLeftArray ConImpLeft(1)];
      TradConImpAIArray=[TradConImpAIArray ConImpAI];
  else
      ModConImpRightArray=[ModConImpRightArray ConImpRight(1)];
      ModConImpLeftArray=[ModConImpLeftArray ConImpLeft(1)];
      ModConImpAIArray=[ModConImpAIArray ConImpAI];
  end

  %Calculate impulse and AI for full eccentric portion
  EccTime=(size(FzRightEcc))*TimeInc;
  EccImpLeft=(mean(FzLeftEcc))*EccTime;
  EccImpRight=(mean(FzRightEcc))*EccTime;
  EccImpComb=EccImpLeft+EccImpRight;
  EccImpAI=((EccImpRight-EccImpLeft)/EccImpComb)*100;

  if j<4
      TradEccImpRightArray=[TradEccImpRightArray EccImpRight(1)];
      TradEccImpLeftArray=[TradEccImpLeftArray EccImpLeft(1)];
      TradEccImpAIArray=[TradEccImpAIArray EccImpAI];
  else
      ModEccImpRightArray=[ModEccImpRightArray EccImpRight(1)];
      ModEccImpLeftArray=[ModEccImpLeftArray EccImpLeft(1)];
      ModEccImpAIArray=[ModEccImpAIArray EccImpAI];
  end

  %Calculate velocity during eccentric phase using first central difference
  EccVel=[];
  TimeInc=1/VideoFrameRate;
  EccC7 = C7_vert(FirstPeak-1:SecondTrough+1);
  EccC7_size = size(EccC7);
  a=1;

  for a=2:EccC7_size-1
     EccVel(a)=((EccC7(a+1))-(EccC7(a-1)))/(2*TimeInc);
  end

  EccVel=EccVel';

 %Find start of braking (deceleration) eccentric phase
 [EccDecFz,EccDecInd]=min(EccVel);

 %Calculate Eccentric deceleration impulse on left and right sides
 %Left side
 EccDecFzLeft=FzLeftEcc(EccDecInd:end);
 EccDecTime=(size(EccDecFzLeft))*TimeInc;
 EccDecFzLeftMean=mean(EccDecFzLeft);
 EccDecImpLeft=EccDecTime(1)*EccDecFzLeftMean;

 %Right side
 EccDecFzRight=FzRightEcc(EccDecInd:end);
```

```
EccDecFzRightMean=mean(EccDecFzRight);
EccDecImpRight=EccDecTime(1)*EccDecFzRightMean;

%Calculate Asymmetry Index
EccDecImpComb=EccDecImpLeft+EccDecImpRight;
EccDecImpAI=((EccDecImpRight-EccDecImpLeft)/EccDecImpComb)*100;
RelativeEccDecImpComb=EccDecImpComb/SWTotal;

if j<4
    TradEccDecImpRightArray=[TradEccDecImpRightArray EccDecImpRight(1)];
    TradEccDecImpLeftArray=[TradEccDecImpLeftArray EccDecImpLeft(1)];
    TradEccDecImpAIArray=[TradEccDecImpAIArray EccDecImpAI];
    TradTotalEccDecImpArray=[TradTotalEccDecImpArray RelativeEccDecImpComb(1)];
else
    ModEccDecImpRightArray=[ModEccDecImpRightArray EccDecImpRight(1)];
    ModEccDecImpLeftArray=[ModEccDecImpLeftArray EccDecImpLeft(1)];
    ModEccDecImpAIArray=[ModEccDecImpAIArray EccDecImpAI];
    ModTotalEccDecImpArray=[ModTotalEccDecImpArray RelativeEccDecImpComb(1)];
end

%Calculate velocity during concentric phase using first central difference
 ConVel=[];
 TimeInc=1/VideoFrameRate;
 ConC7 = C7_vert(SecondTrough-1:SecondPeak+1);
 ConC7_size = size(ConC7);
 b=1;

 for b=2:ConC7_size-1
    ConVel(b)=((ConC7(b+1))-(ConC7(b-1)))/(2*TimeInc);
 end

 ConVel=ConVel';

 %Find end of the acceleration period of the concentric phase by the peak
 %positive velocity
[ConAccFz,ConAccInd]=max(ConVel);

%Calculate Concentric acceleration impulse on left and right sides
%Left side
ConAccFzLeft=FzLeftCon(1:ConAccInd);
ConAccTime=(size(ConAccFzLeft))*TimeInc;
ConAccFzLeftMean=mean(ConAccFzLeft);
ConAccImpLeft=ConAccTime(1)*ConAccFzLeftMean;

%Right side
ConAccFzRight=FzRightCon(1:ConAccInd);
ConAccFzRightMean=mean(ConAccFzRight);
ConAccImpRight=ConAccTime(1)*ConAccFzRightMean;

%Calculate Asymmetry Index
ConAccImpComb=ConAccImpLeft+ConAccImpRight;
ConAccImpAI=((ConAccImpRight-ConAccImpLeft)/ConAccImpComb)*100;

RelativeConAccImpComb=ConAccImpComb/SWTotal;

if j<4
    TradConAccImpRightArray = [TradConAccImpRightArray ConAccImpRight(1)];
    TradConAccImpLeftArray = [TradConAccImpLeftArray ConAccImpLeft(1)];
    TradConAccImpAIArray = [TradConAccImpAIArray ConAccImpAI];
    TradTotalConAccImpArray = [TradTotalConAccImpArray RelativeConAccImpComb(1)];
else
    ModConAccImpRightArray = [ModConAccImpRightArray ConAccImpRight(1)];
```

```
    ModConAccImpLeftArray = [ModConAccImpLeftArray ConAccImpLeft(1)];
    ModConAccImpAIArray = [ModConAccImpAIArray ConAccImpAI];
    ModTotalConAccImpArray = [ModTotalConAccImpArray RelativeConAccImpComb(1)];
end


%%Calculate Asymmetry Index for peak force
%Find peak force during rep for right and left sides
%Left side
[PeakFzLeft, PeakFzLeftId]=max(FzLeftRep);
%Right Side
[PeakFzRight, PeakFzRightId]=max(FzRightRep);
%Calculate combined peak Fz for Asy calculation
PeakFzComb=PeakFzLeft+PeakFzRight;
%Calculate AI
PeakFzAI=((PeakFzRight-PeakFzLeft)/PeakFzComb)*100;

%Calculate bilateral peak force (not the sum)
RelativeBilPeakFz=FzTotal(FirstPeak:SecondPeak)/SWTotal;
[PeakFzBilateral, PeakFzBilateralId]=max(RelativeBilPeakFz);


if j<4
    TradPeakFzRightArray=[TradPeakFzRightArray PeakFzRight(1)];
    TradPeakFzLeftArray=[TradPeakFzLeftArray PeakFzLeft(1)];
    TradPeakFzAIArray=[TradPeakFzAIArray PeakFzAI];
    TradTotalPeakFzArray=[TradTotalPeakFzArray PeakFzBilateral(1)];
else
    ModPeakFzRightArray=[ModPeakFzRightArray PeakFzRight(1)];
    ModPeakFzLeftArray=[ModPeakFzLeftArray PeakFzLeft(1)];
    ModPeakFzAIArray=[ModPeakFzAIArray PeakFzAI];
    ModTotalPeakFzArray=[ModTotalPeakFzArray PeakFzBilateral(1)];
end

%Calculate Time to peak force and Asymmetry Index
TTPFzLeft=PeakFzLeftId*TimeInc;
TTPFzRight=PeakFzRightId*TimeInc;
%Calculate TTP for both sides summated force

if j<4
    TradTTPLeftArray=[TradTTPLeftArray TTPFzLeft];
    TradTTPRightArray=[TradTTPRightArray TTPFzRight];
else
    ModTTPLeftArray=[ModTTPLeftArray TTPFzLeft];
    ModTTPRightArray=[ModTTPRightArray TTPFzRight];
end
end

%Calculate mean values for arrays
TradConImpRightArray = [TradConImpRightArray mean(TradConImpRightArray)];
TradConImpLeftArray = [TradConImpLeftArray mean(TradConImpLeftArray)];
TradConImpAIArray = [TradConImpAIArray mean(TradConImpAIArray)];
ModConImpRightArray = [ModConImpRightArray mean(ModConImpRightArray)];
ModConImpLeftArray = [ModConImpLeftArray mean(ModConImpLeftArray)];
ModConImpAIArray = [ModConImpAIArray mean(ModConImpAIArray)];
TradEccImpRightArray = [TradEccImpRightArray mean(TradEccImpRightArray)];
TradEccImpLeftArray = [TradEccImpLeftArray mean(TradEccImpLeftArray)];
TradEccImpAIArray = [TradEccImpAIArray mean(TradEccImpAIArray)];
ModEccImpRightArray = [ModEccImpRightArray mean(ModEccImpRightArray)];
ModEccImpLeftArray = [ModEccImpLeftArray mean(ModEccImpLeftArray)];
ModEccImpAIArray = [ModEccImpAIArray mean(ModEccImpAIArray)];
TradPeakFzRightArray = [TradPeakFzRightArray mean(TradPeakFzRightArray)];
```

```
TradPeakFzLeftArray = [TradPeakFzLeftArray mean(TradPeakFzLeftArray)];
TradPeakFzAIArray = [TradPeakFzAIArray mean(TradPeakFzAIArray)];
TradTotalPeakFzArray = [TradTotalPeakFzArray mean(TradTotalPeakFzArray)];
ModPeakFzRightArray = [ModPeakFzRightArray mean(ModPeakFzRightArray)];
ModPeakFzLeftArray = [ModPeakFzLeftArray mean(ModPeakFzLeftArray)];
ModPeakFzAIArray = [ModPeakFzAIArray mean(ModPeakFzAIArray)];
ModTotalPeakFzArray= [ModTotalPeakFzArray mean(ModTotalPeakFzArray)];
TradTTPRightArray = [TradTTPRightArray mean(TradTTPRightArray)];
ModTTPRightArray = [ModTTPRightArray mean(ModTTPRightArray)];
TradTTPLeftArray = [TradTTPLeftArray mean(TradTTPLeftArray)];
ModTTPLeftArray = [ModTTPLeftArray mean(ModTTPLeftArray)];
TradEccDecImpRightArray = [TradEccDecImpRightArray mean(TradEccDecImpRightArray)];
TradEccDecImpLeftArray = [TradEccDecImpLeftArray mean(TradEccDecImpLeftArray)];
TradEccDecImpAIArray = [TradEccDecImpAIArray mean(TradEccDecImpAIArray)];
TradTotalEccDecImpArray = [TradTotalEccDecImpArray mean(TradTotalEccDecImpArray)];
ModEccDecImpRightArray = [ModEccDecImpRightArray mean(ModEccDecImpRightArray)];
ModEccDecImpLeftArray = [ModEccDecImpLeftArray mean(ModEccDecImpLeftArray)];
ModEccDecImpAIArray = [ModEccDecImpAIArray mean(ModEccDecImpAIArray)];
ModTotalEccDecImpArray = [ModTotalEccDecImpArray mean(ModTotalEccDecImpArray)];
TradConAccImpRightArray = [TradConAccImpRightArray mean(TradConAccImpRightArray)];
TradConAccImpLeftArray = [TradConAccImpLeftArray mean(TradConAccImpLeftArray)];
TradConAccImpAIArray = [TradConAccImpAIArray mean(TradConAccImpAIArray)];
TradTotalConAccImpArray = [TradTotalConAccImpArray mean(TradTotalConAccImpArray)];
ModConAccImpRightArray = [ModConAccImpRightArray mean(ModConAccImpRightArray)];
ModConAccImpLeftArray = [ModConAccImpLeftArray mean(ModConAccImpLeftArray)];
ModConAccImpAIArray = [ModConAccImpAIArray mean(ModConAccImpAIArray)];
ModTotalConAccImpArray = [ModTotalConAccImpArray mean(ModTotalConAccImpArray)];
TradBWSuppRightArray = [TradBWSuppRightArray mean(TradBWSuppRightArray)];
TradBWSuppLeftArray = [TradBWSuppLeftArray mean(TradBWSuppLeftArray)];
TradBWSuppAIArray = [TradBWSuppAIArray mean(TradBWSuppAIArray)];
TradTotalBWSuppArray = [TradTotalBWSuppArray mean(TradTotalBWSuppArray)];
ModBWSuppRightArray = [ModBWSuppRightArray mean(ModBWSuppRightArray)];
ModBWSuppLeftArray = [ModBWSuppLeftArray mean(ModBWSuppLeftArray)];
ModBWSuppAIArray = [ModBWSuppAIArray mean(ModBWSuppAIArray)];
ModTotalBWSuppArray = [ModTotalBWSuppArray mean(ModTotalBWSuppArray)];

%Turn all arrays into columns
TradConImpRightArray = TradConImpRightArray';
TradConImpLeftArray = TradConImpLeftArray';
TradConImpAIArray = TradConImpAIArray';
ModConImpRightArray = ModConImpRightArray';
ModConImpLeftArray = ModConImpLeftArray';
ModConImpAIArray = ModConImpAIArray';
TradEccImpRightArray = TradEccImpRightArray';
TradEccImpLeftArray = TradEccImpLeftArray';
TradEccImpAIArray = TradEccImpAIArray';
ModEccImpRightArray = ModEccImpRightArray';
ModEccImpLeftArray = ModEccImpLeftArray';
ModEccImpAIArray = ModEccImpAIArray';
TradPeakFzRightArray = TradPeakFzRightArray';
TradPeakFzLeftArray = TradPeakFzLeftArray';
TradPeakFzAIArray = TradPeakFzAIArray';
TradTotalPeakFzArray = TradTotalPeakFzArray';
ModPeakFzRightArray = ModPeakFzRightArray';
ModPeakFzLeftArray = ModPeakFzLeftArray';
ModPeakFzAIArray = ModPeakFzAIArray';
ModTotalPeakFzArray = ModTotalPeakFzArray';
TradTTPRightArray = TradTTPRightArray';
ModTTPRightArray = ModTTPRightArray';
TradTTPLeftArray = TradTTPLeftArray';
ModTTPLeftArray = ModTTPLeftArray';
TradEccDecImpRightArray = TradEccDecImpRightArray';
```

```
TradEccDecImpLeftArray = TradEccDecImpLeftArray';
TradEccDecImpAIArray = TradEccDecImpAIArray';
TradTotalEccDecImpArray = TradTotalEccDecImpArray';
ModEccDecImpRightArray = ModEccDecImpRightArray';
ModEccDecImpLeftArray = ModEccDecImpLeftArray';
ModEccDecImpAIArray = ModEccDecImpAIArray';
ModTotalEccDecImpArray = ModTotalEccDecImpArray';
TradConAccImpRightArray = TradConAccImpRightArray';
TradConAccImpLeftArray = TradConAccImpLeftArray';
TradConAccImpAIArray = TradConAccImpAIArray';
TradTotalConAccImpArray = TradTotalConAccImpArray';
ModConAccImpRightArray = ModConAccImpRightArray';
ModConAccImpLeftArray = ModConAccImpLeftArray';
ModConAccImpAIArray = ModConAccImpAIArray';
ModTotalConAccImpArray = ModTotalConAccImpArray';
TradBWSuppRightArray = TradBWSuppRightArray';
TradBWSuppLeftArray = TradBWSuppLeftArray';
TradBWSuppAIArray = TradBWSuppAIArray';
TradTotalBWSuppArray = TradTotalBWSuppArray';
ModBWSuppRightArray = ModBWSuppRightArray';
ModBWSuppLeftArray = ModBWSuppLeftArray';
ModBWSuppAIArray = ModBWSuppAIArray';
ModTotalBWSuppArray = ModTotalBWSuppArray';
%%Process the Max push-up trials

%Initialize Max arrays
MaxEccImpRight_Array=[];
MaxEccImpLeft_Array=[];
MaxEccImpBAI_Array=[];
MaxEccDecImpRight_Array=[];
MaxEccDecImpLeft_Array=[];
MaxEccDecImpBAI_Array=[];
MaxBilateralEccDecImp_Array=[];
MaxConAccImpRight_Array=[];
MaxConAccImpLeft_Array=[];
MaxConAccImpBAI_Array=[];
MaxBilateralConAccImp_Array=[];
MaxPeakFzRight_Array=[];
MaxPeakFzLeft_Array=[];
MaxPeakFzBAI_Array=[];
MaxBilateralPeakFz_Array=[];
MaxTPFzRight_Array=[];
MaxTPFzLeft_Array=[];
MaxBilateralTPFz_Array=[];
MaxMeanRFDRight_Array=[];
MaxMeanRFDLeft_Array=[];
MaxMeanRFDBAI_Array=[];
MaxBilalteralMeanRFD_Array=[];
MaxEccDecPeakRFDRight_Array=[];
MaxEccDecPeakRFDLeft_Array=[];
MaxEccDecPeakRFDBAI_Array=[];
MaxBilateralEccDecPeakRFD_Array=[];
MaxConAccPeakRFDRight_Array=[];
MaxConAccPeakRFDLeft_Array=[];
MaxConAccPeakRFDBAI_Array=[];
MaxBilateralConAccPeakRFD_Array=[];

MaxTimeSeries=[];
```

Open Max Push-up .c3d file
Do all of the following for each of the three max trials

```
for m=1:3
```

Automated opening of condition 3 trials

```
SubjectIDFileTag=strcat(SubjectID,'_');

CondFileTag='C3_';

if m==1
    TrialFileTag='T1';
elseif m==2
    TrialFileTag='T2';
else
    TrialFileTag='T3';
end

PUfile=strcat(SubjectIDFileTag,CondFileTag,TrialFileTag,'.c3d');
PUfile=char(PUfile);
[Markers,VideoFrameRate,AnalogSignals,AnalogFrameRate,Event,ParameterGroup]=readC3D([subpath
PUfile]);
```

Process C3D file

```
FzLeft=-(AnalogSignals(:,3)); FzRight=-(AnalogSignals(:,9));
C7=Markers(:,1,3);C7_vert=C7/1000; %Put data into arrays
MaxFzLeft_downsample = downsample(FzLeft, 10);
MaxFzRight_downsample = downsample(FzRight, 10);
C7_vert = C7_vert/1000;  %Convert each element from mm to m
MaxFzTotal=MaxFzLeft_downsample+MaxFzRight_downsample;
```

Repitition Isolation

```
%Find where the hands left the ground (Concentric end)
MaxLiftOffId=find(MaxFzTotal<15,1); %(Sha, Z. (2021). BMC Sports Sci Med Rehabil. 13(103))

% Calculate quiet period thresholds
MaxPUFzTotBegMean=mean(MaxFzTotal(1:100));
MaxPUFzSD=std(MaxFzTotal(1:100));

%Find start of the eccentric (unweighting) phase, when force deviates from weight (multiple
options)

MaxCMStartForceThreshold=MaxPUFzTotBegMean-(.05*MaxPUFzTotBegMean); % Fz Change >2.5% body weight
(Barker et al., 2018)
%MaxCMStartId=find(MaxFzTotal<(PUFzTotBegMean-3*PUFzSD),1); %Alternate option using sd

% Find when this decrease persists for more than 25 continiuous data points (.25 sec) to filter
out false starting decreases in quiet phase.
MaxTempStartIdArray=[];
MaxTempStartIdArraySize=size(MaxTempStartIdArray);

s=75; % set time point to start looking for start
f=1;
while MaxTempStartIdArraySize<10
    if MaxFzTotal(s)<MaxCMStartForceThreshold %insert unweighting start indetification option
here
        MaxTempStartIdArray(1,f)=s;
        f=f+1;
    else
        MaxTempStartIdArray=[];
    end
```

```
    s=s+1;
    MaxTempStartIdArraySize=size(MaxTempStartIdArray);
end

MaxCMStartId=s-10;
```

Identify force and C7 trajectory during period of interest

```
MaxPUC7=C7_vert(MaxCMStartId:MaxLiftOffId);
MaxPUFzRight=MaxFzRight_downsample(MaxCMStartId:MaxLiftOffId);
MaxPUFzLeft=MaxFzLeft_downsample(MaxCMStartId:MaxLiftOffId);
MaxBilateralPUFz=MaxPUFzRight+MaxPUFzLeft;
```

Calculate velocity of C7 during entire MAX rep using first central difference

```
 MaxC7Vel=[];
 MaxPUC7Size = size(MaxPUC7);

 for v=2:MaxPUC7Size-1
    MaxC7Vel(v)=((MaxPUC7(v+1))-(MaxPUC7(v-1)))/(2*TimeInc);
 end

 MaxC7Vel=MaxC7Vel';

 %Find the end of the eccentric phase (bottom of countermovement)
 [MaxCMBottom, MaxCMBottomId]=min(MaxPUC7);

 %Find the min velocity (start of the braking phase)
 [MinVel, Max_MinVelId]=min(MaxC7Vel(1:MaxCMBottomId));
 [MaxC7Vel, MaxVelId]=max(MaxC7Vel);
 MaxEccStartId=Max_MinVelId;

 %%Calculate Total eccentric phase impules and AI

 %right side impulse
 MaxEccFzRight=MaxPUFzRight(1:MaxCMBottomId);
 MaxEccTime=(size(MaxEccFzRight))*TimeInc;
 MeanMaxEccFzRight=mean(MaxEccFzRight);
 Max_EccImpRight=MeanMaxEccFzRight*MaxEccTime(1);

 %Left side impulse
 MaxEccFzLeft=MaxPUFzLeft(1:MaxCMBottomId);
 MeanMaxEccFzLeft=mean(MaxEccFzLeft);
 Max_EccImpLeft=MeanMaxEccFzLeft*MaxEccTime(1);

 %Total eccentric phase AI
 MaxEccImpComb=Max_EccImpLeft+Max_EccImpRight;
 MaxEccImpAI=((Max_EccImpRight-Max_EccImpLeft)/MaxEccImpComb)*100;

%%Calculate eccentric deceleration phase impulses and AI
%Right side impulse
MaxEccDecFzRight=MaxPUFzRight(Max_MinVelId:MaxCMBottomId);
MaxEccDecTime=(size(MaxEccDecFzRight))*TimeInc;
MeanMaxEccDecFzRight=mean(MaxEccDecFzRight);
MaxEccDecRightImp=MeanMaxEccDecFzRight*MaxEccDecTime(1);

%Left side impulse
MaxEccDecFzLeft=MaxPUFzLeft(Max_MinVelId:MaxCMBottomId);
MeanMaxEccDecFzLeft=mean(MaxEccDecFzLeft);
MaxEccDecLeftImp=MeanMaxEccDecFzLeft*MaxEccDecTime(1);

%Eccentric Deceleration phase AI
```

```
 MaxEccDecImpComb=MaxEccDecLeftImp+MaxEccDecRightImp;
 MaxEccDecImpAI=((MaxEccDecRightImp-MaxEccDecLeftImp)/MaxEccDecImpComb)*100;

 % Bilateral Eccentric Deceleration impulse
 MaxRelativeBilateralEccDecImp=MaxEccDecImpComb/SWTotal;


 %%Calculate concentric impulse
 %Identify concentric phase

 MaxConAccFzRight=MaxPUFzRight(MaxCMBottomId:end);
 MaxConAccFzLeft=MaxPUFzLeft(MaxCMBottomId:end);

 MaxFzConTot=MaxConAccFzLeft+MaxConAccFzRight;
 ConTime=(size(MaxConAccFzLeft))*TimeInc;
 MeanMaxFzConRight=mean(MaxConAccFzRight);
 MeanMaxFzConLeft=mean(MaxConAccFzLeft);
 MaxConImpRight=MeanMaxFzConRight*ConTime(1);
 MaxConImpLeft=MeanMaxFzConLeft*ConTime(1);
 MaxConImpComb=MaxConImpLeft+MaxConImpRight;
 MaxConImpAI=((MaxConImpRight-MaxConImpLeft)/MaxConImpComb)*100;

 % Bilateral Impulse
 MaxRelativeBilateralConAccImp=MaxConImpComb/SWTotal;

 % Calculate Peak Force impulse
 [MaxPeakFzLeft, MaxPeakFzLeftId]=max(MaxPUFzLeft);
 [MaxPeakFzRight, MaxPeakFzRightId]=max(MaxPUFzRight);
 MaxPeakFzComb=MaxPeakFzRight+MaxPeakFzLeft;
 MaxPeakFzAI=((MaxPeakFzRight-MaxPeakFzLeft)/MaxPeakFzComb)*100;

% Bilateral peak force
[MaxBilateralPeakFz, MaxBilateralPeakFzId]=max(MaxBilateralPUFz);
MaxRelativeBilateralPeakFz=MaxBilateralPeakFz/SWTotal;

% Calculate time to peak for left and right sides (and bilateral)
MaxTPFzRight=MaxPeakFzRightId*TimeInc;
MaxTPFzLeft=MaxPeakFzLeftId*TimeInc;
MaxBilateralTPFz=MaxBilateralPeakFzId*TimeInc;
```

Calculate RFD Variables

```
%Calculate Mean RFD
[Max_UnweightFzLeft, MaxUnweightLeftId]=min(MaxPUFzLeft(1:MaxPeakFzLeftId));
[Max_UnweightFzRight, MaxUnweightRightId]=min(MaxPUFzRight(1:MaxPeakFzRightId));
MaxMRFDLeft=(MaxPeakFzLeft-Max_UnweightFzLeft)/((MaxPeakFzLeftId-MaxUnweightLeftId)*TimeInc);
MaxMRFDRight=(MaxPeakFzRight-Max_UnweightFzRight)/((MaxPeakFzRightId-
MaxUnweightRightId)*TimeInc);

%Calculate Mean RFD AI
MaxMeanRFDComb=MaxMRFDLeft+MaxMRFDRight;
MaxMeanRFDAI = ((MaxMRFDRight-MaxMRFDLeft)/MaxMeanRFDComb)*100;

% Mean bilateral RFD
[Max_UnweightFzBilateral, MaxUnweightBilateralId]=min(MaxFzTotal(1:MaxBilateralPeakFzId));
MaxBilateralMRFD=((MaxBilateralPeakFz-Max_UnweightFzBilateral)/((MaxBilateralPeakFzId-
MaxUnweightBilateralId)*TimeInc));
MaxRelativeBilateralMRFD=MaxBilateralMRFD/SWTotal;
```

Calculate peak rate of force development (PeakRFD)

```
MaxBilateralEccDecFz=MaxConAccFzRight+MaxConAccFzLeft;
```

```
MaxBilateralConAccFz=MaxConAccFzRight+MaxConAccFzLeft;

MaxEccDecFzRight_size=size(MaxEccDecFzRight); % find length of the Fz array
MaxEccDecFzLeft_size=size(MaxEccDecFzLeft);
MaxEccDecFzBilateral_size=size(MaxBilateralEccDecFz);

MaxConAccFzRight_size=size(MaxConAccFzRight);
MaxConAccFzLeft_size=size(MaxConAccFzLeft);
MaxConAccFzBilateral_size=size(MaxBilateralConAccFz);
```

Eccentric braking right

```
k=1;
MaxEccDecPeakRFD_Right=[];

for k=2:MaxEccDecFzRight_size(1)
    MaxEccDecPeakRFD_Right(k)=(MaxEccDecFzRight(k)-MaxEccDecFzRight(k-1))/(1/100);
end
MaxEccDecPeakRFD_Right=max(MaxEccDecPeakRFD_Right);
```

Eccentric braking left

```
k=1;
MaxEccDecPeakRFD_Left=[];

for k=2:MaxEccDecFzLeft_size(1)
    MaxEccDecPeakRFD_Left(k)=(MaxEccDecFzLeft(k)-MaxEccDecFzLeft(k-1))/(1/100);
end
MaxEccDecPeakRFD_Left=max(MaxEccDecPeakRFD_Left);
```

Bilateral Eccentric Braking PeakRFD

```
k=1;
MaxBilateralEccDecPeakRFD=[];

for k=2:MaxEccDecFzBilateral_size(1)
    MaxBilateralEccDecPeakRFD(k)=(MaxBilateralEccDecFz(k)-MaxBilateralEccDecFz(k-1))/(1/100);
end
MaxBilateralEccDecPeakRFD=max(MaxBilateralEccDecPeakRFD);
MaxRelativeBilateralEccDecPeakRFD=MaxBilateralEccDecPeakRFD/SWTotal;
```

Eccentric braking BAI

```
MaxEccDecPeakRFDBAI=((MaxEccDecPeakRFD_Right-
MaxEccDecPeakRFD_Left)/(MaxEccDecPeakRFD_Right+MaxEccDecPeakRFD_Left))*100;
```

Concentric acceleration phase Peak RFD

```
% right
k=1;
MaxConAccPeakRFD_Right=[];

for k=2:MaxConAccFzRight_size(1)
    MaxConAccPeakRFD_Right(k)=(MaxConAccFzRight(k)-MaxConAccFzRight(k-1))/(1/100);
end
MaxConAccPeakRFD_Right=max(MaxConAccPeakRFD_Right);

% left
k=1;
MaxConAccPeakRFD_Left=[];

for k=2:MaxConAccFzLeft_size(1)
```

```
    MaxConAccPeakRFD_Left(k)=(MaxConAccFzLeft(k)-MaxConAccFzLeft(k-1))/(1/100);
end
MaxConAccPeakRFD_Left=max(MaxConAccPeakRFD_Left);
```

Bilateral Concentric Peak RFD

```
k=1;
MaxBilateralConAccPeakRFD=[];

for k=2:MaxConAccFzBilateral_size(1)
    MaxBilateralConAccPeakRFD(k)=(MaxBilateralConAccFz(k)-MaxBilateralConAccFz(k-1))/(1/100);
end
MaxBilateralConAccPeakRFD=max(MaxBilateralConAccPeakRFD);
MaxRelativeBilateralConAccPeakRFD=MaxBilateralConAccPeakRFD/SWTotal;
```

Concentric acceleration Peak RFD BAI

```
MaxConAccPeakRFDBAI=((MaxConAccPeakRFD_Right-
MaxConAccPeakRFD_Left)/(MaxConAccPeakRFD_Right+MaxConAccPeakRFD_Left))*100;
```

Load variables into their arrays

```
MaxEccImpRight_Array=[MaxEccImpRight_Array Max_EccImpRight];
MaxEccImpLeft_Array=[MaxEccImpLeft_Array Max_EccImpLeft];
MaxEccImpBAI_Array=[MaxEccImpBAI_Array  MaxEccImpAI];

MaxEccDecImpRight_Array=[MaxEccDecImpRight_Array MaxEccDecRightImp];
MaxEccDecImpLeft_Array=[MaxEccDecImpLeft_Array MaxEccDecLeftImp];
MaxEccDecImpBAI_Array=[MaxEccDecImpBAI_Array MaxEccDecImpAI];
MaxBilateralEccDecImp_Array=[MaxBilateralEccDecImp_Array MaxRelativeBilateralEccDecImp];

MaxConAccImpRight_Array=[MaxConAccImpRight_Array MaxConImpRight];
MaxConAccImpLeft_Array=[MaxConAccImpLeft_Array MaxConImpLeft];
MaxConAccImpBAI_Array=[MaxConAccImpBAI_Array MaxConImpAI];
MaxBilateralConAccImp_Array=[MaxBilateralConAccImp_Array MaxRelativeBilateralConAccImp];

MaxPeakFzRight_Array=[MaxPeakFzRight_Array MaxPeakFzRight];
MaxPeakFzLeft_Array=[MaxPeakFzLeft_Array MaxPeakFzLeft];
MaxPeakFzBAI_Array=[MaxPeakFzBAI_Array MaxPeakFzAI];
MaxBilateralPeakFz_Array=[MaxBilateralPeakFz_Array MaxRelativeBilateralPeakFz];

MaxTPFzRight_Array=[MaxTPFzRight_Array MaxTPFzRight];
MaxTPFzLeft_Array=[MaxTPFzLeft_Array MaxTPFzLeft];
MaxBilateralTPFz_Array=[MaxBilateralTPFz_Array MaxBilateralTPFz];

MaxMeanRFDRight_Array=[MaxMeanRFDRight_Array MaxMRFDRight];
MaxMeanRFDLeft_Array=[MaxMeanRFDLeft_Array MaxMRFDLeft];
MaxMeanRFDBAI_Array=[MaxMeanRFDBAI_Array MaxMeanRFDAI];
MaxBilalteralMeanRFD_Array=[MaxBilalteralMeanRFD_Array MaxRelativeBilateralMRFD];

MaxEccDecPeakRFDRight_Array=[MaxEccDecPeakRFDRight_Array MaxEccDecPeakRFD_Right];
MaxEccDecPeakRFDLeft_Array=[MaxEccDecPeakRFDLeft_Array MaxEccDecPeakRFD_Left];
MaxEccDecPeakRFDBAI_Array=[MaxEccDecPeakRFDBAI_Array MaxEccDecPeakRFDBAI];
MaxBilateralEccDecPeakRFD_Array=[MaxBilateralEccDecPeakRFD_Array
MaxRelativeBilateralEccDecPeakRFD];

MaxConAccPeakRFDRight_Array=[MaxConAccPeakRFDRight_Array MaxConAccPeakRFD_Right];
MaxConAccPeakRFDLeft_Array=[MaxConAccPeakRFDLeft_Array MaxConAccPeakRFD_Left];
MaxConAccPeakRFDBAI_Array=[MaxConAccPeakRFDBAI_Array MaxConAccPeakRFDBAI];
MaxBilateralConAccPeakRFD_Array=[MaxBilateralConAccPeakRFD_Array
MaxRelativeBilateralConAccPeakRFD];
```

```
%establish points to plot
MaxTTB=MaxCMBottomId*TimeInc;
MaxFABRight=MaxPUFzRight(MaxCMBottomId);
MaxFABLeft=MaxPUFzLeft(MaxCMBottomId);
TTPLeft=MaxPeakFzLeftId*TimeInc;
TTPRight=MaxPeakFzRightId*TimeInc;

%Create max time series
MaxPUFzLeftSize=size(MaxPUFzLeft, 1);
for t=1:MaxPUFzLeftSize
    if t==1
        MaxTimeSeries(t)=0;
    else
    MaxTimeSeries(t)=(t-1)*TimeInc;
    end
end
MaxTimeSeries=MaxTimeSeries';
MaxTimeSeries=MaxTimeSeries(1:MaxPUFzLeftSize);

%Plot data to check
figure;
title(strcat(SubjectIDFileTag,CondFileTag,TrialFileTag)) % Added by TW

yyaxis left;
plot(MaxTimeSeries, MaxPUFzLeft);
hold on;
plot(MaxTimeSeries,MaxPUFzRight);
hold on;

yyaxis right;
plot(MaxTimeSeries,MaxPUC7);
ylabel ('C7 Trajectory (m)')
xlabel('Time (s)')
hold on;

yyaxis left;
% plot(MaxTTB, MaxFABRight, 'ko');
% hold on;
% plot(MaxTTB, MaxFABLeft, 'bo');
% hold on;
plot(TTPRight, MaxPeakFzRight, 'ms');
hold on;
plot(TTPLeft, MaxPeakFzLeft, 'bs');
ylabel('GRF (N)')
hold on;

%With FAB
% legend('GRF Left','GRF Right', 'FAB Right', 'FAB Left', 'Peak Force Right', 'Peak Force Left',
'C7 Position','Location','southeast'); % designate the plot legend text and location

% Without FAB
legend('GRF Left','GRF Right','Peak Force Right', 'Peak Force Left', 'C7
Position','Location','southeast'); % designate the plot legend text and location


m=m+1;
```

```
end

%Calculate and load the mean into the arrays
```

```
MaxEccImpRight_Array=[MaxEccImpRight_Array mean(MaxEccImpRight_Array)];
MaxEccImpLeft_Array=[MaxEccImpLeft_Array mean(MaxEccImpLeft_Array)];
MaxEccImpBAI_Array=[MaxEccImpBAI_Array  mean(MaxEccImpBAI_Array)];

MaxEccDecImpRight_Array=[MaxEccDecImpRight_Array mean(MaxEccDecImpRight_Array)];
MaxEccDecImpLeft_Array=[MaxEccDecImpLeft_Array mean(MaxEccDecImpLeft_Array)];
MaxEccDecImpBAI_Array=[MaxEccDecImpBAI_Array mean(MaxEccDecImpBAI_Array)];
MaxBilateralEccDecImp_Array=[MaxBilateralEccDecImp_Array mean(MaxBilateralEccDecImp_Array)];

MaxConAccImpRight_Array=[MaxConAccImpRight_Array mean(MaxConAccImpRight_Array)];
MaxConAccImpLeft_Array=[MaxConAccImpLeft_Array mean(MaxConAccImpLeft_Array)];
MaxConAccImpBAI_Array=[MaxConAccImpBAI_Array mean(MaxConAccImpBAI_Array)];
MaxBilateralConAccImp_Array=[MaxBilateralConAccImp_Array mean(MaxBilateralConAccImp_Array)];

MaxPeakFzRight_Array=[MaxPeakFzRight_Array mean(MaxPeakFzRight_Array)];
MaxPeakFzLeft_Array=[MaxPeakFzLeft_Array mean(MaxPeakFzLeft_Array)];
MaxPeakFzBAI_Array=[MaxPeakFzBAI_Array mean(MaxPeakFzBAI_Array)];
MaxBilateralPeakFz_Array=[MaxBilateralPeakFz_Array mean(MaxBilateralPeakFz_Array)];

MaxTPFzRight_Array=[MaxTPFzRight_Array mean(MaxTPFzRight_Array)];
MaxTPFzLeft_Array=[MaxTPFzLeft_Array mean(MaxTPFzLeft_Array)];
MaxBilateralTPFz_Array=[MaxBilateralTPFz_Array mean(MaxBilateralTPFz_Array)];

MaxMeanRFDRight_Array=[MaxMeanRFDRight_Array mean(MaxMeanRFDRight_Array)];
MaxMeanRFDLeft_Array=[MaxMeanRFDLeft_Array mean(MaxMeanRFDLeft_Array)];
MaxMeanRFDBAI_Array=[MaxMeanRFDBAI_Array mean(MaxMeanRFDBAI_Array)];
MaxBilalteralMeanRFD_Array=[MaxBilalteralMeanRFD_Array mean(MaxBilalteralMeanRFD_Array)];

MaxEccDecPeakRFDRight_Array=[MaxEccDecPeakRFDRight_Array mean(MaxEccDecPeakRFDRight_Array)];
MaxEccDecPeakRFDLeft_Array=[MaxEccDecPeakRFDLeft_Array mean(MaxEccDecPeakRFDLeft_Array)];
MaxEccDecPeakRFDBAI_Array=[MaxEccDecPeakRFDBAI_Array mean(MaxEccDecPeakRFDBAI_Array)];
MaxBilateralEccDecPeakRFD_Array=[MaxBilateralEccDecPeakRFD_Array
mean(MaxBilateralEccDecPeakRFD_Array)];

MaxConAccPeakRFDRight_Array=[MaxConAccPeakRFDRight_Array mean(MaxConAccPeakRFDRight_Array)];
MaxConAccPeakRFDLeft_Array=[MaxConAccPeakRFDLeft_Array mean(MaxConAccPeakRFDLeft_Array)];
MaxConAccPeakRFDBAI_Array=[MaxConAccPeakRFDBAI_Array mean(MaxConAccPeakRFDBAI_Array)];
MaxBilateralConAccPeakRFD_Array=[MaxBilateralConAccPeakRFD_Array
mean(MaxBilateralConAccPeakRFD_Array)];


%Turn all arrays into columns

MaxEccImpRight_Array=MaxEccImpRight_Array';
MaxEccImpLeft_Array=MaxEccImpLeft_Array';
MaxEccImpBAI_Array=MaxEccImpBAI_Array';

MaxEccDecImpRight_Array=MaxEccDecImpRight_Array';
MaxEccDecImpLeft_Array=MaxEccDecImpLeft_Array';
MaxEccDecImpBAI_Array=MaxEccDecImpBAI_Array';
MaxBilateralEccDecImp_Array=MaxBilateralEccDecImp_Array';

MaxConAccImpRight_Array=MaxConAccImpRight_Array';
MaxConAccImpLeft_Array=MaxConAccImpLeft_Array';
MaxConAccImpBAI_Array=MaxConAccImpBAI_Array';
MaxBilateralConAccImp_Array=MaxBilateralConAccImp_Array';

MaxPeakFzRight_Array=MaxPeakFzRight_Array';
MaxPeakFzLeft_Array=MaxPeakFzLeft_Array';
MaxPeakFzBAI_Array=MaxPeakFzBAI_Array';
MaxBilateralPeakFz_Array=MaxBilateralPeakFz_Array';
```

```
MaxTPFzRight_Array=MaxTPFzRight_Array';
MaxTPFzLeft_Array=MaxTPFzLeft_Array';
MaxBilateralTPFz_Array=MaxBilateralTPFz_Array';

MaxMeanRFDRight_Array=MaxMeanRFDRight_Array';
MaxMeanRFDLeft_Array=MaxMeanRFDLeft_Array';
MaxMeanRFDBAI_Array=MaxMeanRFDBAI_Array';
MaxBilalteralMeanRFD_Array=MaxBilalteralMeanRFD_Array';

MaxEccDecPeakRFDRight_Array=MaxEccDecPeakRFDRight_Array';
MaxEccDecPeakRFDLeft_Array=MaxEccDecPeakRFDLeft_Array';
MaxEccDecPeakRFDBAI_Array=MaxEccDecPeakRFDBAI_Array';
MaxBilateralEccDecPeakRFD_Array=MaxBilateralEccDecPeakRFD_Array';

MaxConAccPeakRFDRight_Array=MaxConAccPeakRFDRight_Array';
MaxConAccPeakRFDLeft_Array=MaxConAccPeakRFDLeft_Array';
MaxConAccPeakRFDBAI_Array=MaxConAccPeakRFDBAI_Array';
MaxBilateralConAccPeakRFD_Array=MaxBilateralConAccPeakRFD_Array';

%%Arrange Data Arrays
%Row label array
Row_labels=["1", "2", "3", "Mean"]';

%%Prepare data in Arrays for export
Trad_Array=[Row_labels, TradBWSuppRightArray, TradBWSuppLeftArray, TradBWSuppAIArray,
TradEccDecImpRightArray, TradEccDecImpLeftArray, TradEccDecImpAIArray, TradConAccImpRightArray,
TradConAccImpLeftArray, TradConAccImpAIArray, TradPeakFzRightArray, TradPeakFzLeftArray,
TradPeakFzAIArray, TradTotalBWSuppArray, TradTotalEccDecImpArray, TradTotalConAccImpArray,
TradTotalPeakFzArray];
Mod_Array=[Row_labels, ModBWSuppRightArray, ModBWSuppLeftArray, ModBWSuppAIArray,
ModEccDecImpRightArray, ModEccDecImpLeftArray, ModEccDecImpAIArray, ModConAccImpRightArray,
ModConAccImpLeftArray, ModConAccImpAIArray, ModPeakFzRightArray, ModPeakFzLeftArray,
ModPeakFzAIArray, ModTotalBWSuppArray, ModTotalEccDecImpArray, ModTotalConAccImpArray,
ModTotalPeakFzArray];
Max_Array=[Row_labels, MaxMeanRFDRight_Array, MaxMeanRFDLeft_Array, MaxMeanRFDBAI_Array,
MaxEccDecImpRight_Array, MaxEccDecImpLeft_Array, MaxEccDecImpBAI_Array, MaxConAccImpRight_Array,
MaxConAccImpLeft_Array, MaxConAccImpBAI_Array, MaxPeakFzRight_Array, MaxPeakFzLeft_Array,
MaxPeakFzBAI_Array, MaxTPFzRight_Array, MaxTPFzLeft_Array, MaxEccDecPeakRFDRight_Array,
MaxEccDecPeakRFDLeft_Array, MaxEccDecPeakRFDBAI_Array, MaxConAccPeakRFDRight_Array,
MaxConAccPeakRFDLeft_Array, MaxConAccPeakRFDBAI_Array, MaxBilateralEccDecImp_Array,
MaxBilateralConAccImp_Array, MaxBilateralPeakFz_Array, MaxBilateralTPFz_Array,
MaxBilalteralMeanRFD_Array, MaxBilateralEccDecPeakRFD_Array, MaxBilateralConAccPeakRFD_Array];

%Find sizes of the data arrays for each condition
Trad_Array_size=size(Trad_Array);
Mod_Array_size=size(Mod_Array);
Max_Array_size=size(Max_Array);

%%Construct Trad and Mod Heading
row=1;col=1;

heading{row,col}='Trials'; col=col+1;
heading{row,col}='Body Weight Supported Right (N)'; col=col+1;
heading{row,col}='Body Weight Supported Left (N)'; col=col+1;
heading{row,col}='Body Weight Supported BAI'; col=col+1;
% heading{row,col}='Eccentric Impulse Right (Ns)'; col=col+1;
% heading{row,col}='Eccentric Impulse Left (Ns)'; col=col+1;
% heading{row,col}='Eccentric Impulse AI'; col=col+1;
heading{row,col}='Ecc Dec Impulse Right (Ns)'; col=col+1;
heading{row,col}='Ecc Dec Impulse Left (Ns)'; col=col+1;
heading{row,col}='Ecc Dec Impulse BAI'; col=col+1;
```

```
% heading{row,col}='Concentric Impulse Right (Ns)'; col=col+1;
% heading{row,col}='Concentric Impulse Left (Ns)'; col=col+1;
% heading{row,col}='Concentric Impulse AI'; col=col+1;
heading{row,col}='Con Acc Impulse Right (Ns)'; col=col+1;
heading{row,col}='Con Acc Impulse Left (Ns)'; col=col+1;
heading{row,col}='Con Acc Impulse AI'; col=col+1;
heading{row,col}='Peak Force Right (N)'; col=col+1;
heading{row,col}='Peak Force Left (N)'; col=col+1;
heading{row,col}='Peak Force BAI'; col=col+1;
heading{row,col}='Relative Total Body Weight Supported (BW)'; col=col+1;
heading{row,col}='Relative Eccentric Deceleration Total Impulse (BW*s)'; col=col+1;
heading{row,col}='Relative Concentric Acceleration Total Impulse (BW*s)'; col=col+1;
heading{row,col}='Relative Bilateral Peak Force (BW)'; col=col+1;
% heading{row,col}='Time to Peak Right (s)'; col=col+1;
% heading{row,col}='Time to Peak Left (s)'; col=col+1;
row=row+1;col=1;

%%Construct max Heading
row=1;col=1;

%heading{row,col}='Trial'; col=col+1;
% heading{row,col}='Trials'; col=col+1;
MaxHeading{row,col}='Trials'; col=col+1;
MaxHeading{row,col}='Mean RFD Right (N/s)'; col=col+1;
MaxHeading{row,col}='Mean RFD Left (N/s)'; col=col+1;
MaxHeading{row,col}='Mean RFD BAI'; col=col+1;
% MaxHeading{row,col}='Eccentric Impulse Right (Ns)'; col=col+1;
% MaxHeading{row,col}='Eccentric Impulse Left (Ns)'; col=col+1;
% MaxHeading{row,col}='Eccentric Impulse AI'; col=col+1;
MaxHeading{row,col}='Eccentric Dec Impulse Right (Ns)'; col=col+1;
MaxHeading{row,col}='Eccentric Dec Impulse Left (Ns)'; col=col+1;
MaxHeading{row,col}='Eccentric Dec Impulse BAI'; col=col+1;
MaxHeading{row,col}='Concentric Acc Impulse Right (Ns)'; col=col+1;
MaxHeading{row,col}='Concentric Acc Impulse Left (Ns)'; col=col+1;
MaxHeading{row,col}='Concentric Acc Impulse AI'; col=col+1;
MaxHeading{row,col}='Peak Force Right (N)'; col=col+1;
MaxHeading{row,col}='Peak Force Left (N)'; col=col+1;
MaxHeading{row,col}='Peak Force AI'; col=col+1;
MaxHeading{row,col}='Time to Peak Right (s)'; col=col+1;
MaxHeading{row,col}='Time to Peak Left (s)'; col=col+1;
MaxHeading{row,col}='Eccentric Dec Peak RFD Right (N/s)'; col=col+1;
MaxHeading{row,col}='Eccentric Dec Peak RFD Left (N/s)'; col=col+1;
MaxHeading{row,col}='Eccentric Dec Peak RFD BAI'; col=col+1;
MaxHeading{row,col}='Concentric Acc Peak RFD Right (N/s)'; col=col+1;
MaxHeading{row,col}='Concentric Acc Peak RFD Left (N/s)'; col=col+1;
MaxHeading{row,col}='Concentric Acc Peak RFD BAI'; col=col+1;
MaxHeading{row,col}='Relative Eccentric Deceleration Total Impulse (BW*s)'; col=col+1;
MaxHeading{row,col}='Relative Concentric Acceleration Total Impulse (BW*s)'; col=col+1;
MaxHeading{row,col}='Relative Total Peak Force (BW)'; col=col+1;
MaxHeading{row,col}='Total Time to Peak (s)'; col=col+1;
MaxHeading{row,col}='Relative Total Mean RFD (BW/s)'; col=col+1;
MaxHeading{row,col}='Relative Total Eccentric Deceleration Peak RFD (BW/s)'; col=col+1;
MaxHeading{row,col}='Relative Total Concentric Acc Peak RFD (BW/s)'; col=col+1;
row=row+1;col=1;
```

Construct Output Array for Reporting Data

```
%Construct main file heading
col=1; row=1;
```

```
output_array{row,col}=SubjectID; row=row+1;
output_array{row,col}='Push-up Asymmetry Data Summary'; row=row+2;

% Demographics
% output_array{row,col}='Demographics'; row=row+1;
% output_array{row,col}='Gender'; col=col+1;
% output_array{row,col}='Age'; col=col+1;
% output_array{row,col}='Height (m)'; col=col+1;
output_array{row,col}='Standing Body Weight (N)'; col=col+1;
output_array{row,col}='Body Mass (kg)'; col=col+1;
% output_array{row,col}='Handedness'; col=col+1;
% output_array{row,col}='Push-up Body Weight (N)';
row=row+1;col=1;
% output_array{row,col}=Gender; col=col+1;
% output_array{row,col}=str2double(age); col=col+1;
% output_array{row,col}=Height_m; col=col+1;
output_array{row,col}=SWTotal; col=col+1;
output_array{row,col}=SWTotal/9.806; col=col+1;
% output_array{row,col}=handdom; col=col+1;
% output_array{row,col}=PUBW; col=1;
row=row+2; col=1;

output_array{row,col}='Push-up Asymmetry Results Across Conditions';row=row+2;
col=1;

%Trad Data
output_array{row,col}='Traditional Push-up Data'; row=row+1;

%Insert heading above Trad data
a=size(heading,2);
col=1;
for i=1:a
    output_array{row, col}=heading(i);
    col=col+1;
end
row=row+1;

%Insert Trad_Array into output array
for i=1:Trad_Array_size(1)
    col=1;
    for j=1:Trad_Array_size(2)
     output_array{row,col}=Trad_Array(i,j);
     col=col+1;
    end
    row=row+1;
end
row=row+1;
col=1;

%Mod Data
output_array{row,col}='Modified Push-up Data'; row=row+1;

%Insert heading above Mod data
a=size(heading,2);
col=1;
for i=1:a
    output_array{row, col}=heading(i);
    col=col+1;
end
row=row+1;

%Insert Mod_Array into output array
```

```
for i=1:Mod_Array_size(1)
    col=1;
    for j=1:Mod_Array_size(2)
     output_array{row,col}=Mod_Array(i,j);
     col=col+1;
    end
    row=row+1;
end
row=row+1;
col=1;

%Max Data
output_array{row,col}='Max Push-up Data'; row=row+1;

%Insert heading above Max data
a=size(MaxHeading,2);
col=1;
for i=1:a
    output_array{row, col}=MaxHeading(i);
    col=col+1;
end
row=row+1;

%Insert Max_Array into output array
for i=1:Max_Array_size(1)
    col=1;
    for j=1:Max_Array_size(2)
     output_array{row,col}=Max_Array(i,j);
     col=col+1;
    end
    row=row+1;
end
row=row+1;
col=1;
%Prepare output array for saving, since it contains nested cell arrays
for i=1:size(output_array, 1)
    for j=1:size(output_array, 2)
        if iscell(output_array{i,j})
            output_array{i,j} = output_array{i,j}{:};
        end
    end
end
```

Save data summaries seperatly in each subject folder

```
savefilename=strcat(path, SubjectID);
savefilename=strcat(savefilename,' Push-up Asymmetry Data Summary.csv');
savefilename=char(savefilename);
writecell(output_array, savefilename);
```

Save data summaries all together in one folder

```
summarypath=strcat(path,'\','Data Summaries','\');
savefilename=strcat(summarypath, SubjectID);
savefilename=strcat(savefilename,' Push-up Asymmetry Data Summary.csv');
savefilename=char(savefilename);
writecell(output_array, savefilename);

subject+1;
end
```

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Appendix C: SPSS Syntax and Statistical Output

```
*SPSS syntax for push-up asymmetry study 2023
   *Script assembled by Taylor Walston using SPSS V28.0.1.0
```

```
*Descriptive Statistics for subject characteristics

DATASET ACTIVATE DataSet1.
T-TEST GROUPS=Sex(1 2)
  /MISSING=ANALYSIS
  /VARIABLES=Age Height Weight
  /ES DISPLAY(TRUE)
  /CRITERIA=CI(.95).

*2x2 two-way mixed ANOVA with repeated measures
   Push-up starting posture X participant sex on WtD BAIABS.

GLM WtDBSI_MOD WtDBSI_TRAD BY Sex
  /WSFACTOR=Variation 2 POLYNOMIAL
  /MEASURE=WtD_BSI
  /METHOD=SSTYPE(3)
  /PLOT=PROFILE(Variation*Sex) TYPE=LINE ERRORBAR=CI MEANREFERENCE=NO YAXIS=AUTO
  /EMMEANS=TABLES(OVERALL)
  /EMMEANS=TABLES(Sex) COMPARE ADJ(BONFERRONI)
  /EMMEANS=TABLES(Variation) COMPARE ADJ(BONFERRONI)
  /EMMEANS=TABLES(Sex*Variation) COMPARE(Sex) ADJ(BONFERRONI)
  /EMMEANS=TABLES(Sex*Variation) COMPARE(Variation) ADJ(BONFERRONI)
  /PRINT=DESCRIPTIVE ETASQ OPOWER HOMOGENEITY
  /CRITERIA=ALPHA(.05)
  /WSDESIGN=Variation
  /DESIGN=Sex.

*2x3 two-way mixed ANOVA with repeated measures
   Push-up variation X participant sex on peak vGRF BAIABS.

DATASET ACTIVATE DataSet1.
GLM PeakVGRFBSI_MOD PeakVGRFBSI_TRAD PeakVGRFBSI_MAX BY Sex
  /WSFACTOR=Variation 3 POLYNOMIAL
  /MEASURE=Peak_VGRF_BSI
  /METHOD=SSTYPE(3)
  /PLOT=PROFILE(Variation*Sex) TYPE=LINE ERRORBAR=CI MEANREFERENCE=NO YAXIS=AUTO
  /EMMEANS=TABLES(OVERALL)
  /EMMEANS=TABLES(Sex) COMPARE ADJ(BONFERRONI)
  /EMMEANS=TABLES(Variation) COMPARE ADJ(BONFERRONI)
  /EMMEANS=TABLES(Sex*Variation) COMPARE(Sex) ADJ(BONFERRONI)
  /EMMEANS=TABLES(Sex*Variation) COMPARE(Variation) ADJ(BONFERRONI)
  /PRINT=DESCRIPTIVE ETASQ OPOWER HOMOGENEITY
  /CRITERIA=ALPHA(.05)
  /WSDESIGN=Variation
  /DESIGN=Sex.
```

```
*2x3 two-way mixed ANOVA with repeated measures
  Push-up variation X participant sex on eccentric deceleration impulse BAIABS.

GLM EccDecImpBSI_MOD EccDecImpBSI_TRAD EccDecImpBSI_MAX BY Sex
 /WSFACTOR=Variation 3 POLYNOMIAL
 /MEASURE=Eccentric_Impulse_BSI
 /METHOD=SSTYPE(3)
 /PLOT=PROFILE(Variation*Sex) TYPE=LINE ERRORBAR=CI MEANREFERENCE=NO YAXIS=AUTO
 /EMMEANS=TABLES(OVERALL)
 /EMMEANS=TABLES(Sex) COMPARE ADJ(BONFERRONI)
 /EMMEANS=TABLES(Variation) COMPARE ADJ(BONFERRONI)
 /EMMEANS=TABLES(Sex*Variation) COMPARE(Sex) ADJ(BONFERRONI)
 /EMMEANS=TABLES(Sex*Variation) COMPARE(Variation) ADJ(BONFERRONI)
 /PRINT=DESCRIPTIVE ETASQ OPOWER HOMOGENEITY
 /CRITERIA=ALPHA(.05)
 /WSDESIGN=Variation
 /DESIGN=Sex.

*2x3 two-way mixed ANOVA with repeated measures
  Push-up variation X participant sex on concentric acceleration impulse BAIABS.

GLM ConAccImpBSI_MOD ConAccImpBSI_TRAD ConAccImpBSI_MAX BY Sex
 /WSFACTOR=Variation 3 POLYNOMIAL
 /MEASURE=Concentric_Impulse_BSI
 /METHOD=SSTYPE(3)
 /PLOT=PROFILE(Variation*Sex) TYPE=LINE ERRORBAR=CI MEANREFERENCE=NO YAXIS=AUTO
 /EMMEANS=TABLES(OVERALL)
 /EMMEANS=TABLES(Sex) COMPARE ADJ(BONFERRONI)
 /EMMEANS=TABLES(Variation) COMPARE ADJ(BONFERRONI)
 /EMMEANS=TABLES(Sex*Variation) COMPARE(Sex) ADJ(BONFERRONI)
 /EMMEANS=TABLES(Sex*Variation) COMPARE(Variation) ADJ(BONFERRONI)
 /PRINT=DESCRIPTIVE ETASQ OPOWER HOMOGENEITY
 /CRITERIA=ALPHA(.05)
 /WSDESIGN=Variation
 /DESIGN=Sex.

DATASET ACTIVATE DataSet1.
T-TEST GROUPS=Sex(1 2)
 /MISSING=ANALYSIS
 /VARIABLES=Mean_RFD_MAX EccDecPeak_RFD_MAX ConAccPeak_RFD_MAX
 /ES DISPLAY(TRUE)
 /CRITERIA=CI(.95).

*Post hoc tests for significant main effects T-

TEST GROUPS=Sex(1 2)
 /MISSING=ANALYSIS
 /VARIABLES=EccDecImpBSI_TRAD
 /ES DISPLAY(TRUE)
 /CRITERIA=CI(.95).

T-TEST GROUPS=Sex(1 2)
```

```
  /MISSING=ANALYSIS
  /VARIABLES=WtDBSI_TRAD
  /ES DISPLAY(TRUE)
  /CRITERIA=CI(.95).

*Descriptive statistics for power related variables

DATASET ACTIVATE DataSet1.
DESCRIPTIVES VARIABLES=EccDecPeak_RFD_MAX ConAccPeak_RFD_MAX Mean_RFD_MAX
  /STATISTICS=MEAN STDDEV MIN MAX.

*Levene's test correction via Welch's Test and Brown-Forsythe Test ONEWAY

WtDBSI_TRAD BY Sex
  /STATISTICS HOMOGENEITY BROWNFORSYTHE WELCH
  /MISSING ANALYSIS
  /CRITERIA=CILEVEL(0.95).
```

SPSS Statistical Output

Participant Demographics:

Group Statistics

	Sex	N	Mean	Std. Deviation	Std. Error Mean
Age	Male	17	21.94	2.015	.489
	Female	10	20.30	1.059	.335
Height	Male	17	177.3994	5.22390	1.26698
	Female	10	164.5310	4.07883	1.28984
Weight	Male	17	82.4621	13.95207	3.38387
	Female	10	65.9228	11.21885	3.54771

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means							
						Significance				95% Confidence Interval of the Difference	
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
Age	Equal variances assumed	1.609	.216	2.377	25	.013	.025	1.641	.690	.219	3.063
	Equal variances not assumed			2.770	24.825	.005	.010	1.641	.592	.421	2.862
Height	Equal variances assumed	.055	.817	6.667	25	<.001	<.001	12.86841	1.93005	8.89340	16.84342
	Equal variances not assumed			7.117	22.804	<.001	<.001	12.86841	1.80802	9.12647	16.61036
Weight	Equal variances assumed	.154	.698	3.184	25	.002	.004	16.53937	5.19452	5.84106	27.23768
	Equal variances not assumed			3.373	22.397	.001	.003	16.53937	4.90274	6.38216	26.69658

Independent Samples Effect Sizes

		Standardizer[a]	Point Estimate	95% Confidence Interval Lower	Upper
Age	Cohen's d	1.733	.947	.115	1.762
	Hedges' correction	1.787	.919	.112	1.709
	Glass's delta	1.059	1.549	.474	2.578
Height	Cohen's d	4.84296	2.657	1.572	3.714
	Hedges' correction	4.99457	2.576	1.524	3.601
	Glass's delta	4.07883	3.155	1.506	4.768
Weight	Cohen's d	13.03431	1.269	.402	2.114
	Hedges' correction	13.44234	1.230	.390	2.050
	Glass's delta	11.21885	1.474	.422	2.481

a. The denominator used in estimating the effect sizes.
Cohen's d uses the pooled standard deviation.
Hedges' correction uses the pooled standard deviation, plus a correction factor.
Glass's delta uses the sample standard deviation of the control group.

Weight Distribution Asymmetry 2x2 Repeated Measures ANOVA:

Descriptive Statistics

	Sex	Mean	Std. Deviation	N
WtDBSI_MOD	Male	3.2676	2.28775	17
	Female	4.4630	3.20258	10
	Total	3.7104	2.66780	27
WtDBSI_TRAD	Male	1.7934	1.48992	17
	Female	4.2497	3.71819	10
	Total	2.7031	2.75909	27

Box's Test of Equality of Covariance Matrices[a]

Box's M	11.504
F	3.464
df1	3
df2	10957.743
Sig.	.016

Tests the null hypothesis that the observed covariance matrices of the dependent variables are equal across groups.

a. Design: Intercept + Sex
 Within Subjects Design: Variation

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[c]
Variation	Pillai's Trace	.050	1.308[b]	1.000	25.000	.264	.050	1.308	.196
	Wilks' Lambda	.950	1.308[b]	1.000	25.000	.264	.050	1.308	.196
	Hotelling's Trace	.052	1.308[b]	1.000	25.000	.264	.050	1.308	.196
	Roy's Largest Root	.052	1.308[b]	1.000	25.000	.264	.050	1.308	.196
Variation * Sex	Pillai's Trace	.028	.730[b]	1.000	25.000	.401	.028	.730	.130
	Wilks' Lambda	.972	.730[b]	1.000	25.000	.401	.028	.730	.130
	Hotelling's Trace	.029	.730[b]	1.000	25.000	.401	.028	.730	.130
	Roy's Largest Root	.029	.730[b]	1.000	25.000	.401	.028	.730	.130

a. Design: Intercept + Sex

Within Subjects Design: Variation

b. Exact statistic

c. Computed using alpha = .05

Mauchly's Test of Sphericity[a]

Measure: WtD_BSI

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Epsilon[b] Huynh-Feldt	Epsilon[b] Lower-bound
Variation	1.000	.000	0	.	1.000	1.000	1.000

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + Sex
Within Subjects Design: Variation

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: WtD_BSI

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Variation	Sphericity Assumed	8.965	1	8.965	1.308	.264	.050	1.308	.196
	Greenhouse-Geisser	8.965	1.000	8.965	1.308	.264	.050	1.308	.196
	Huynh-Feldt	8.965	1.000	8.965	1.308	.264	.050	1.308	.196
	Lower-bound	8.965	1.000	8.965	1.308	.264	.050	1.308	.196
Variation * Sex	Sphericity Assumed	5.004	1	5.004	.730	.401	.028	.730	.130
	Greenhouse-Geisser	5.004	1.000	5.004	.730	.401	.028	.730	.130
	Huynh-Feldt	5.004	1.000	5.004	.730	.401	.028	.730	.130
	Lower-bound	5.004	1.000	5.004	.730	.401	.028	.730	.130
Error(Variation)	Sphericity Assumed	171.310	25	6.852					
	Greenhouse-Geisser	171.310	25.000	6.852					
	Huynh-Feldt	171.310	25.000	6.852					
	Lower-bound	171.310	25.000	6.852					

a. Computed using alpha = .05

Levene's Test of Equality of Error Variances[a]

		Levene Statistic	df1	df2	Sig.
WtDBSI_MOD	Based on Mean	1.278	1	25	.269
	Based on Median	.730	1	25	.401
	Based on Median and with adjusted df	.730	1	21.440	.402
	Based on trimmed mean	1.315	1	25	.262
WtDBSI_TRAD	Based on Mean	5.269	1	25	.030
	Based on Median	5.113	1	25	.033
	Based on Median and with adjusted df	5.113	1	13.133	.041
	Based on trimmed mean	5.138	1	25	.032

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Sex

Within Subjects Design: Variation

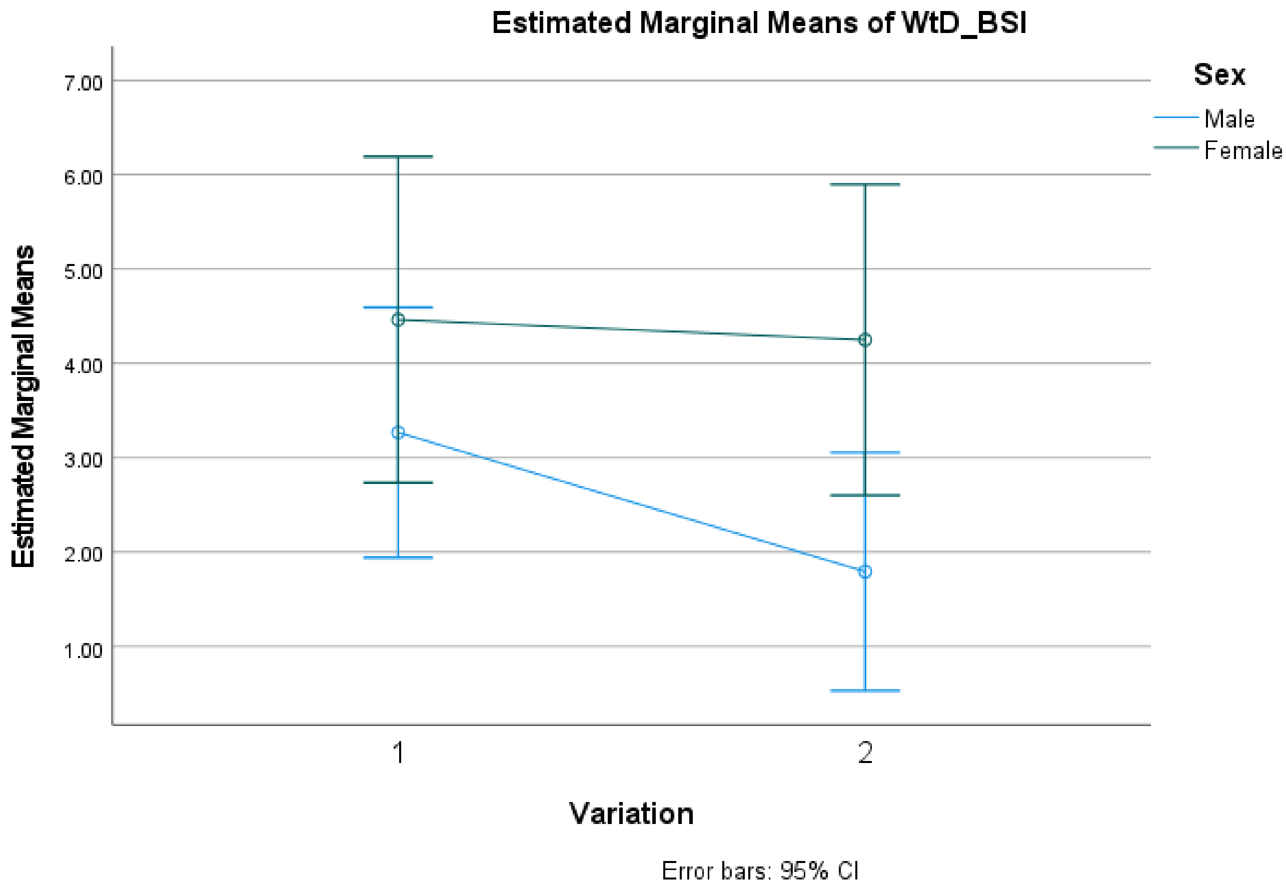
Tests of Between-Subjects Effects

Measure: WtD_BSI

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Intercept	597.252	1	597.252	90.668	<.001	.784	90.668	1.000
Sex	41.978	1	41.978	6.373	.018	.203	6.373	.680
Error	164.682	25	6.587					

a. Computed using alpha = .05


Estimated Marginal Means of WtD_BSI
Sex
Male
Female
Estimated Marginal Means
7.00
6.00
5.00
4.00
3.00
2.00
1.00
1
2
Variation
Error bars: 95% CI

Peak vGRF Asymmetry 2x3 Repeated Measures ANOVA:

Descriptive Statistics

	Sex	Mean	Std. Deviation	N
PeakVGRFBSI_MOD	Male	2.3121	1.82138	17
	Female	1.1441	.74734	10
	Total	1.8795	1.60161	27
PeakVGRFBSI_TRAD	Male	2.1146	1.67801	17
	Female	1.6052	1.04712	10
	Total	1.9259	1.47483	27
PeakVGRFBSI_MAX	Male	2.1609	1.61749	17
	Female	2.5503	2.51919	10
	Total	2.3051	1.96050	27

Box's Test of Equality of Covariance Matrices[a]

Box's M	13.018
F	1.850
df1	6
df2	2306.367
Sig.	.086

Tests the null hypothesis that the observed covariance matrices of the dependent variables are equal across groups.

a. Design: Intercept + Sex
Within Subjects Design: Variation

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[c]
Variation	Pillai's Trace	.077	1.002[b]	2.000	24.000	.382	.077	2.004	.204
	Wilks' Lambda	.923	1.002[b]	2.000	24.000	.382	.077	2.004	.204
	Hotelling's Trace	.084	1.002[b]	2.000	24.000	.382	.077	2.004	.204
	Roy's Largest Root	.084	1.002[b]	2.000	24.000	.382	.077	2.004	.204
Variation * Sex	Pillai's Trace	.145	2.031[b]	2.000	24.000	.153	.145	4.063	.377
	Wilks' Lambda	.855	2.031[b]	2.000	24.000	.153	.145	4.063	.377
	Hotelling's Trace	.169	2.031[b]	2.000	24.000	.153	.145	4.063	.377
	Roy's Largest Root	.169	2.031[b]	2.000	24.000	.153	.145	4.063	.377

a. Design: Intercept + Sex
 Within Subjects Design: Variation

b. Exact statistic

c. Computed using alpha = .05

Mauchly's Test of Sphericity[a]

Measure: Peak_VGRF_BSI

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Variation	.501	16.598	2	<.001	.667	.719	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + Sex

Within Subjects Design: Variation

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Peak_VGRF_BSI

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Variation	Sphericity Assumed	5.515	2	2.757	1.696	.194	.064	3.392	.340
	Greenhouse-Geisser	5.515	1.334	4.134	1.696	.203	.064	2.262	.276
	Huynh-Feldt	5.515	1.437	3.837	1.696	.202	.064	2.438	.286
	Lower-bound	5.515	1.000	5.515	1.696	.205	.064	1.696	.240
Variation * Sex	Sphericity Assumed	7.695	2	3.848	2.366	.104	.086	4.733	.457
	Greenhouse-Geisser	7.695	1.334	5.768	2.366	.126	.086	3.157	.366
	Huynh-Feldt	7.695	1.437	5.353	2.366	.122	.086	3.401	.381
	Lower-bound	7.695	1.000	7.695	2.366	.137	.086	2.366	.316
Error(Variation)	Sphericity Assumed	81.300	50	1.626					
	Greenhouse-Geisser	81.300	33.351	2.438					
	Huynh-Feldt	81.300	35.936	2.262					
	Lower-bound	81.300	25.000	3.252					

a. Computed using alpha = .05

Levene's Test of Equality of Error Variances[a]

		Levene Statistic	df1	df2	Sig.
PeakVGRFBSI_MOD	Based on Mean	6.014	1	25	.022
	Based on Median	5.641	1	25	.026
	Based on Median and with adjusted df	5.641	1	18.363	.029
	Based on trimmed mean	5.795	1	25	.024
PeakVGRFBSI_TRAD	Based on Mean	2.960	1	25	.098
	Based on Median	.831	1	25	.371
	Based on Median and with adjusted df	.831	1	19.387	.373
	Based on trimmed mean	2.570	1	25	.122
PeakVGRFBSI_MAX	Based on Mean	1.174	1	25	.289
	Based on Median	.168	1	25	.685
	Based on Median and with adjusted df	.168	1	17.229	.687
	Based on trimmed mean	.629	1	25	.435

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Sex

Within Subjects Design: Variation

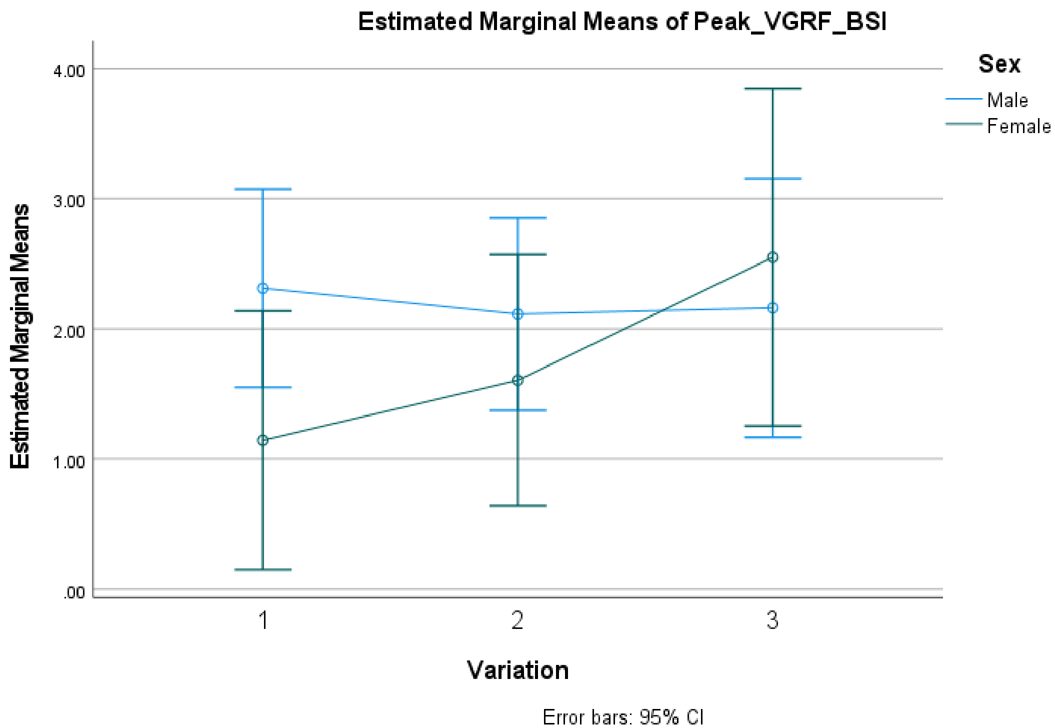
Tests of Between-Subjects Effects

Measure: Peak_VGRF_BSI

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Intercept	296.565	1	296.565	56.725	<.001	.694	56.725	1.000
Sex	3.482	1	3.482	.666	.422	.026	.666	.123
Error	130.703	25	5.228					

a. Computed using alpha = .05



Eccentric Deceleration Impulse Asymmetry 2x3 Repeated Measures ANOVA:

Descriptive Statistics

	Sex	Mean	Std. Deviation	N
EccDecImpBSI_MOD	Male	2.2496	1.36423	17
	Female	1.5997	1.02353	10
	Total	2.0089	1.26895	27
EccDecImpBSI_TRAD	Male	2.1452	1.16630	17
	Female	.7774	.68758	10
	Total	1.6386	1.20574	27
EccDecImpBSI_MAX	Male	1.9118	1.62484	17
	Female	1.6591	1.37732	10
	Total	1.8182	1.51552	27

Box's Test of Equality of Covariance Matrices[a]

Box's M	8.482
F	1.205
df1	6
df2	2306.367
Sig.	.300

Tests the null hypothesis that the observed covariance matrices of the dependent variables are equal across groups.

a. Design: Intercept + Sex
Within Subjects Design: Variation

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[c]
Variation	Pillai's Trace	.089	1.169[b]	2.000	24.000	.328	.089	2.337	.232
	Wilks' Lambda	.911	1.169[b]	2.000	24.000	.328	.089	2.337	.232
	Hotelling's Trace	.097	1.169[b]	2.000	24.000	.328	.089	2.337	.232
	Roy's Largest Root	.097	1.169[b]	2.000	24.000	.328	.089	2.337	.232
Variation * Sex	Pillai's Trace	.105	1.415[b]	2.000	24.000	.262	.105	2.830	.273
	Wilks' Lambda	.895	1.415[b]	2.000	24.000	.262	.105	2.830	.273
	Hotelling's Trace	.118	1.415[b]	2.000	24.000	.262	.105	2.830	.273
	Roy's Largest Root	.118	1.415[b]	2.000	24.000	.262	.105	2.830	.273

a. Design: Intercept + Sex

Within Subjects Design: Variation

b. Exact statistic

c. Computed using alpha = .05

Mauchly's Test of Sphericity[a]

Measure: Eccentric_Impulse_BSI

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Variation	.952	1.192	2	.551	.954	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + Sex

Within Subjects Design: Variation

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Eccentric_Impulse_BSI

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Variation	Sphericity Assumed	2.847	2	1.424	.950	.394	.037	1.899	.206
	Greenhouse-Geisser	2.847	1.908	1.493	.950	.390	.037	1.811	.201
	Huynh-Feldt	2.847	2.000	1.424	.950	.394	.037	1.899	.206
	Lower-bound	2.847	1.000	2.847	.950	.339	.037	.950	.155
Variation * Sex	Sphericity Assumed	4.023	2	2.011	1.342	.271	.051	2.683	.276
	Greenhouse-Geisser	4.023	1.908	2.109	1.342	.271	.051	2.559	.270
	Huynh-Feldt	4.023	2.000	2.011	1.342	.271	.051	2.683	.276
	Lower-bound	4.023	1.000	4.023	1.342	.258	.051	1.342	.200
Error(Variation)	Sphericity Assumed	74.956	50	1.499					
	Greenhouse-Geisser	74.956	47.690	1.572					
	Huynh-Feldt	74.956	50.000	1.499					
	Lower-bound	74.956	25.000	2.998					

a. Computed using alpha = .05

Levene's Test of Equality of Error Variances[a]

		Levene Statistic	df1	df2	Sig.
EccDecImpBSI_MOD	Based on Mean	1.236	1	25	.277
	Based on Median	1.546	1	25	.225
	Based on Median and with adjusted df	1.546	1	24.703	.225
	Based on trimmed mean	1.287	1	25	.267
EccDecImpBSI_TRAD	Based on Mean	2.428	1	25	.132
	Based on Median	2.484	1	25	.128
	Based on Median and with adjusted df	2.484	1	23.261	.129
	Based on trimmed mean	2.878	1	25	.102
EccDecImpBSI_MAX	Based on Mean	.599	1	25	.446
	Based on Median	.576	1	25	.455
	Based on Median and with adjusted df	.576	1	24.999	.455
	Based on trimmed mean	.680	1	25	.417

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Sex

Within Subjects Design: Variation

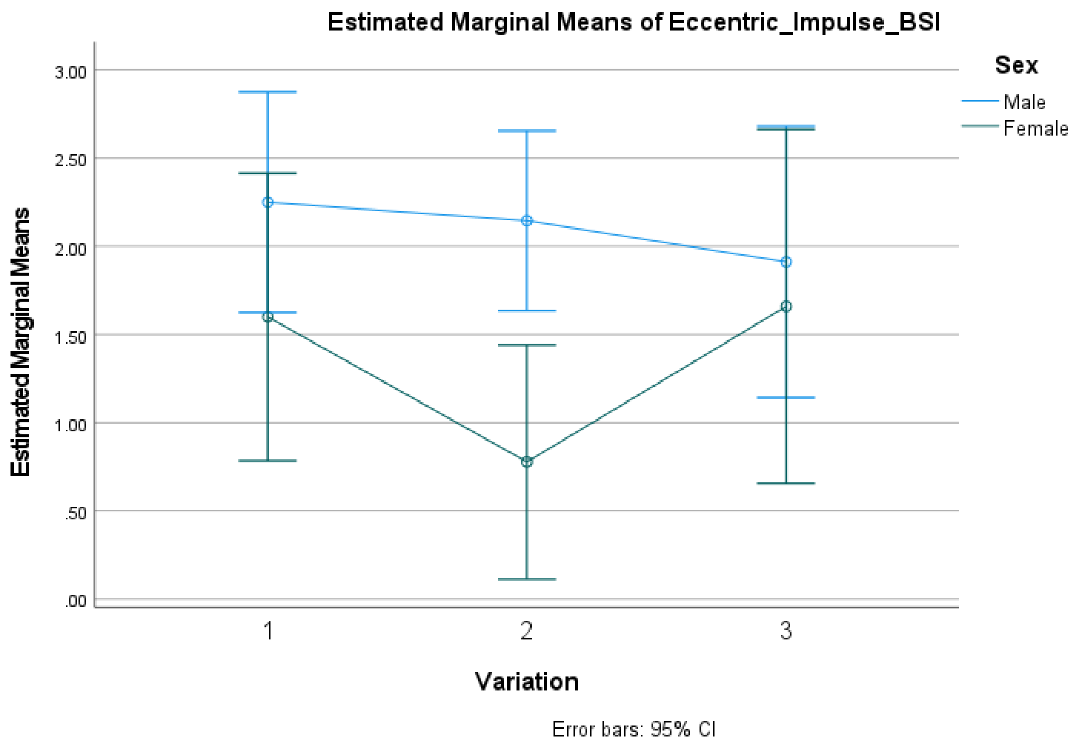
Tests of Between-Subjects Effects

Measure: Eccentric_Impulse_BSI

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Intercept	224.515	1	224.515	113.199	<.001	.819	113.199	1.000
Sex	10.819	1	10.819	5.455	.028	.179	5.455	.612
Error	49.584	25	1.983					

a. Computed using alpha = .05



Concentric Acceleration Impulse Asymmetry 2x3 Repeated Measures ANOVA:

Descriptive Statistics

	Sex	Mean	Std. Deviation	N
ConAccImpBSI_MOD	Male	1.9533	1.57020	17
	Female	1.4171	.89578	10
	Total	1.7547	1.36551	27
ConAccImpBSI_TRAD	Male	1.7525	1.42232	17
	Female	1.9878	1.92790	10
	Total	1.8396	1.59528	27
ConAccImpBSI_MAX	Male	1.9252	1.28580	17
	Female	2.6950	2.50882	10
	Total	2.2103	1.82747	27

Box's Test of Equality of Covariance Matrices[a]

Box's M	28.839
F	4.098
df1	6
df2	2306.367
Sig.	<.001

Tests the null hypothesis that the observed covariance matrices of the dependent variables are equal across groups.

a. Design: Intercept + Sex
 Within Subjects Design: Variation

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[c]
Variation	Pillai's Trace	.108	1.446[b]	2.000	24.000	.255	.108	2.893	.279
	Wilks' Lambda	.892	1.446[b]	2.000	24.000	.255	.108	2.893	.279
	Hotelling's Trace	.121	1.446[b]	2.000	24.000	.255	.108	2.893	.279
	Roy's Largest Root	.121	1.446[b]	2.000	24.000	.255	.108	2.893	.279
Variation * Sex	Pillai's Trace	.118	1.610[b]	2.000	24.000	.221	.118	3.219	.306
	Wilks' Lambda	.882	1.610[b]	2.000	24.000	.221	.118	3.219	.306
	Hotelling's Trace	.134	1.610[b]	2.000	24.000	.221	.118	3.219	.306
	Roy's Largest Root	.134	1.610[b]	2.000	24.000	.221	.118	3.219	.306

a. Design: Intercept + Sex
Within Subjects Design: Variation

b. Exact statistic

c. Computed using alpha = .05

Mauchly's Test of Sphericity[a]

Measure: Concentric_Impulse_BSI

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Variation	.796	5.481	2	.065	.830	.918	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + Sex
 Within Subjects Design: Variation

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Concentric_Impulse_BSI

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Variation	Sphericity Assumed	5.191	2	2.595	2.147	.128	.079	4.293	.419
	Greenhouse-Geisser	5.191	1.661	3.125	2.147	.137	.079	3.565	.379
	Huynh-Feldt	5.191	1.836	2.828	2.147	.132	.079	3.941	.400
	Lower-bound	5.191	1.000	5.191	2.147	.155	.079	2.147	.291
Variation * Sex	Sphericity Assumed	5.428	2	2.714	2.245	.117	.082	4.490	.436
	Greenhouse-Geisser	5.428	1.661	3.268	2.245	.127	.082	3.728	.394
	Huynh-Feldt	5.428	1.836	2.957	2.245	.121	.082	4.121	.416
	Lower-bound	5.428	1.000	5.428	2.245	.147	.082	2.245	.302
Error(Variation)	Sphericity Assumed	60.450	50	1.209					
	Greenhouse-Geisser	60.450	41.522	1.456					
	Huynh-Feldt	60.450	45.892	1.317					
	Lower-bound	60.450	25.000	2.418					

a. Computed using alpha = .05

Levene's Test of Equality of Error Variances[a]

		Levene Statistic	df1	df2	Sig.
ConAccImpBSI_MOD	Based on Mean	3.017	1	25	.095
	Based on Median	2.932	1	25	.099
	Based on Median and with adjusted df	2.932	1	20.698	.102
	Based on trimmed mean	2.951	1	25	.098
ConAccImpBSI_TRAD	Based on Mean	.789	1	25	.383
	Based on Median	.533	1	25	.472
	Based on Median and with adjusted df	.533	1	23.316	.473
	Based on trimmed mean	.713	1	25	.406
ConAccImpBSI_MAX	Based on Mean	3.540	1	25	.072
	Based on Median	2.192	1	25	.151
	Based on Median and with adjusted df	2.192	1	16.273	.158
	Based on trimmed mean	3.169	1	25	.087

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Sex

Within Subjects Design: Variation

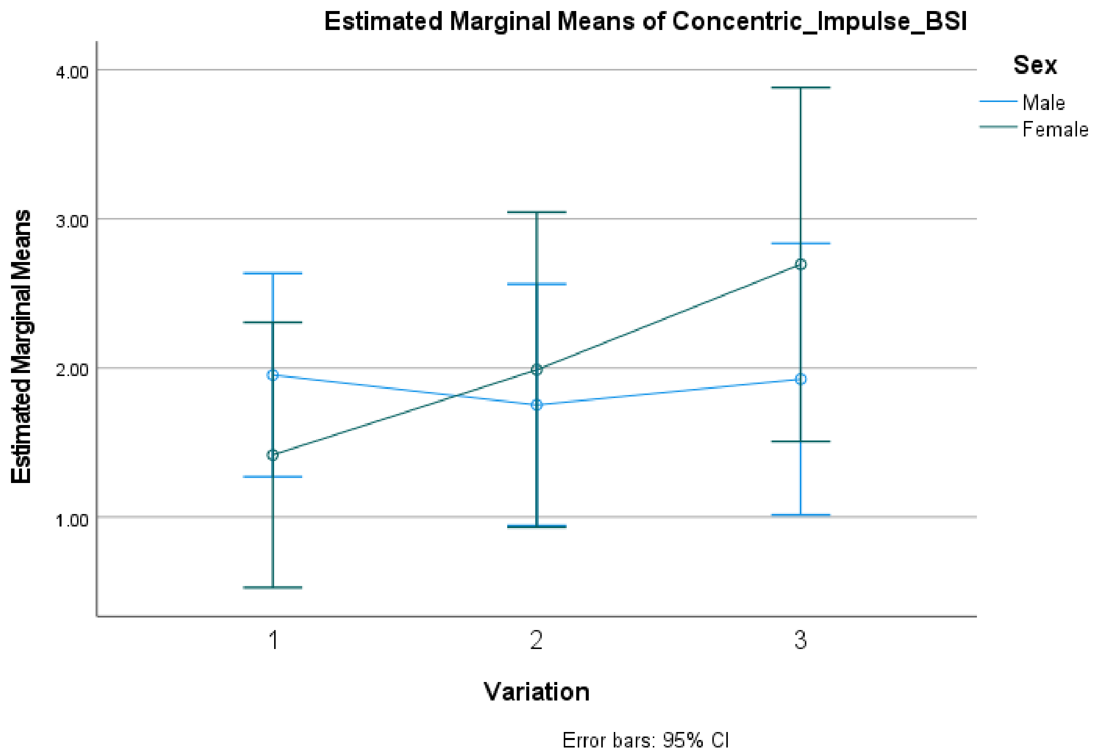
Tests of Between-Subjects Effects

Measure: Concentric_Impulse_BSI

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Intercept	288.817	1	288.817	53.429	<.001	.681	53.429	1.000
Sex	.462	1	.462	.085	.773	.003	.085	.059
Error	135.140	25	5.406					

a. Computed using alpha = .05



Between Groups T-tests for Power Related Variables:

Group Statistics

	Sex	N	Mean	Std. Deviation	Std. Error Mean
Mean_RFD_MAX	Male	17	5.3723	5.76233	1.39757
	Female	10	5.8752	6.14545	1.94336
EccDecPeak_RFD_MAX	Male	17	6.4751	3.36379	.81584
	Female	10	6.6859	4.17975	1.32175
ConAccPeak_RFD_MAX	Male	17	12.8319	6.25777	1.51773
	Female	10	8.7055	6.46745	2.04519

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means							
						Significance				95% Confidence Interval of the Difference	
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
Mean_RFD_MAX	Equal variances assumed	.778	.386	-.214	25	.416	.832	-.50280	2.35255	-5.34797	4.34237
	Equal variances not assumed			-.210	18.007	.418	.836	-.50280	2.39371	-5.53166	4.52606
EccDecPeak_RFD_MAX	Equal variances assumed	.305	.585	-.144	25	.443	.887	-.21079	1.46596	-3.22999	2.80842
	Equal variances not assumed			-.136	15.868	.447	.894	-.21079	1.55326	-3.50578	3.08421
ConAccPeak_RFD_MAX	Equal variances assumed	.217	.646	1.635	25	.057	.115	4.12639	2.52429	-1.07248	9.32526
	Equal variances not assumed			1.620	18.488	.061	.122	4.12639	2.54682	-1.21417	9.46695

Independent Samples Effect Sizes

		Standardizer[a]	Point Estimate	95% Confidence Interval	
				Lower	Upper
Mean_RFD_MAX	Cohen's d	5.90312	-.085	-.866	.697
	Hedges' correction	6.08792	-.083	-.840	.676
	Glass's delta	6.14545	-.082	-.862	.702
EccDecPeak_RFD_MAX	Cohen's d	3.67845	-.057	-.838	.725
	Hedges' correction	3.79360	-.056	-.813	.703
	Glass's delta	4.17975	-.050	-.830	.732
ConAccPeak_RFD_MAX	Cohen's d	6.33405	.651	-.156	1.447
	Hedges' correction	6.53234	.632	-.151	1.403
	Glass's delta	6.46745	.638	-.211	1.456

a. The denominator used in estimating the effect sizes.

Cohen's d uses the pooled standard deviation.

Hedges' correction uses the pooled standard deviation, plus a correction factor.

Glass's delta uses the sample standard deviation of the control group.

Unequal Variance Adjustments:

Group Statistics

	Sex	N	Mean	Std. Deviation	Std. Error Mean
EccDecImpBSI_TRAD	Male	17	2.1452	1.16630	.28287
	Female	10	.7774	.68758	.21743

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means							
						Significance				95% Confidence Interval of the Difference	
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
EccDecImpBSI_TRAD	Equal variances assumed	2.428	.132	3.364	25	.001	.002	1.36783	.40657	.53049	2.20518
	Equal variances not assumed			3.834	24.986	<.001	<.001	1.36783	.35678	.63301	2.10266

Independent Samples Effect Sizes

		Standardizer[a]	Point Estimate	95% Confidence Interval Lower	95% Confidence Interval Upper
EccDecImpBSI_TRAD	Cohen's d	1.02018	1.341	.466	2.194
	Hedges' correction	1.05212	1.300	.451	2.127
	Glass's delta	.68758	1.989	.772	3.162

a. The denominator used in estimating the effect sizes.

Cohen's d uses the pooled standard deviation.

Hedges' correction uses the pooled standard deviation, plus a correction factor.

Glass's delta uses the sample standard deviation of the control group.

Group Statistics

	Sex	N	Mean	Std. Deviation	Std. Error Mean
WtDBSI_TRAD	Male	17	1.7934	1.48992	.36136
	Female	10	4.2497	3.71819	1.17580

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means							
						Significance				95% Confidence Interval of the Difference	
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
WtDBSI_TRAD	Equal variances assumed	5.269	.030	-2.437	25	.011	.022	-2.45622	1.00802	-4.53227	-.38016
	Equal variances not assumed			-1.997	10.727	.036	.072	-2.45622	1.23007	-5.17203	.25960

Independent Samples Effect Sizes

		Standardizer[a]	Point Estimate	95% Confidence Interval	
				Lower	Upper
WtDBSI_TRAD	Cohen's d	2.52937	-.971	-1.788	-.137
	Hedges' correction	2.60855	-.942	-1.734	-.133
	Glass's delta	3.71819	-.661	-1.482	.192

a. The denominator used in estimating the effect sizes.
Cohen's d uses the pooled standard deviation.
Hedges' correction uses the pooled standard deviation, plus a correction factor.
Glass's delta uses the sample standard deviation of the control group.

Tests of Homogeneity of Variances

		Levene Statistic	df1	df2	Sig.
WtDBSI_TRAD	Based on Mean	5.269	1	25	.030
	Based on Median	5.113	1	25	.033
	Based on Median and with adjusted df	5.113	1	13.133	.041
	Based on trimmed mean	5.138	1	25	.032

ANOVA

WtDBSI_TRAD

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	37.986	1	37.986	5.937	.022
Within Groups	159.942	25	6.398		
Total	197.928	26			

Robust Tests of Equality of Means

WtDBSI_TRAD

	Statistic[a]	df1	df2	Sig.
Welch	3.987	1	10.727	.072
Brown-Forsythe	3.987	1	10.727	.072

a. Asymptotically F distributed.

Appendix D: Participant Data

Average individual participant vGRF kinetic asymmetry data.

						Ecc dec impulse BAI			Con acc impulse BAI			Peak vGRF BAI			WtD BAI	
Subject ID	Age	Sex	Height	Handedness	Subject mass (kg)	MOD	TRAD	MAX	MOD	TRAD	MAX	MOD	TRAD	MAX	MOD	TRAD
1	21	1	178.5	1	91.94480811	-0.45869	1.1109	0.63097	-0.83818	-0.078514	-0.42503	-0.49548	0.91944	0.34641	-1.7928	0.48252
2	22	1	177.625	1	123.730785	-1.7731	0.84618	0.061671	-0.37786	1.1962	-1.3996	-0.66713	1.1837	0.66787	2.4193	-1.7533
3	20	2	159.25	1	58.37665953	-1.182	0.446	-0.86853	-1.5271	-2.1701	-2.8004	-0.97324	-0.26361	0.4137	-5.07566	-4.2063
4	22	1	182	1	78.49930326	-1.2259	-2.4254	-4.7764	0.25533	-0.88995	0.14204	-0.43988	-1.5346	-2.0736	-0.82956	-2.6374
5	21	2	162.25	1	58.79977041	3.3383	0.351	0.38455	2.0758	-0.46365	2.2253	1.6323	-0.98349	1.6596	4.9551	3.7054
6	27	1	177.875	1	88.33157532	3.1591	1.9433	2.0808	2.6378	1.0276	1.1874	2.4115	1.3252	2.1982	1.8246	0.8278
7	19	2	164.5	1	67.96519493	-1.643	-0.59886	-2.5397	-1.2003	0.29153	-1.1237	-1.4961	2.6959	1.7103	-2.5555	-11.1753
8	20	1	177.875	1	68.79658227	2.066	1.5448	1.1403	0.099818	0.66773	3.3744	-0.14654	0.54787	2.3426	2.898	-1.8676
9	21	2	169.875	1	83.34941179	-1.1105	-2.3493	-4.5976	-2.6439	-5.8597	-8.0302	-1.5355	-3.1632	-8.8381	0.50535	-2.5304
10	23	1	175	1	72.00770794	-0.2807	-2.8354	-0.15373	0.92573	-0.79434	1.5236	0.6838	-1.4757	1.1167	1.5515	0.47293
11	21	1	184.875	2	77.3807735	-0.093714	2.9698	0.041598	-1.9838	1.6153	5.1502	-2.1699	1.1451	3.5003	5.5579	2.4282
12	20	2	165.75	1	76.69015385	-0.97545	-0.094054	3.0266	0.51082	0.90435	0.40031	0.94656	1.7147	4.8862	2.9755	0.6348
13	21	2	169.875	1	65.38181623	0.61846	0.51885	1.1066	2.8063	4.7987	6.1175	-0.016242	2.5726	1.918	9.1901	1.0478
14	21	1	183.875	1	79.94635721	-1.0406	-2.2029	-2.1641	-2.4231	-2.7665	-1.1731	-2.1371	-3.2691	-2.1296	-3.8495	-1.0047
15	22	1	175.375	1	82.77441101	-1.4606	0.72517	-3.4451	-0.17788	0.45327	-1.1026	-0.32322	-0.36444	-0.86037	-4.124	-0.6753
16	21	1	164.375	1	74.94865545	3.5277	0.66421	2.6056	2.4659	1.8105	2.2549	3.3816	2.4098	2.2883	9.96249	1.976
17	19	2	165.25	1	76.4145082	0.49825	-0.13582	1.7055	-0.35969	-1.7688	-1.5373	-0.054689	0.50591	2.2389	-2.0881	0.089674
18	24	1	178	2	74.15964806	-4.5288	-2.8134	-0.5006	-5.2445	-3.2086	-1.985	-6.2226	-4.863	-1.2869	-6.11686	-0.50196
19	20	1	170	1	60.32110303	-2.4347	-2.8094	0.15393	-2.9536	-3.8985	-0.50325	-4.1334	-5.0033	-0.61166	-0.92423	0.25319
20	21	2	160.75	1	60.20799178	-0.99861	-1.3579	-0.56072	-1.1425	-0.91204	0.76083	-1.8183	-1.8389	-1.7909	-2.9841	-4.2961
21	26	1	175.5	1	96.00228634	2.7068	2.2452	4.1753	3.7774	1.8082	3.0413	3.9666	3.7331	6.8903	2.9195	-0.23463
22	21	1	173.375	1	91.27654932	-3.5909	-0.53622	-1.4337	-1.2023	0.67006	-1.5595	-1.4036	0.10905	-1.5496	-4.1199	-5.0735
23	19	2	168.5	1	67.47045892	3.044	1.1963	1.5638	1.6032	0.31916	0.8837	0.67836	0.30482	0.62052	3.5755	9.92155
24	20	1	185.1	1	76.73010861	-2.2628	3.1861	2.0649	-1.1808	2.8293	3.2506	-2.6275	1.7232	3.5314	-2.9103	4.7971
25	22	2	159.3	1	44.57182923	-2.5882	0.72575	-0.23773	-0.30158	2.3897	3.0708	-2.2898	2.0087	1.4266	-10.7253	-4.8892
26	21	1	178.9	1	78.40407198	3.6677	5.0455	2.2855	4.7674	5.3609	2.9207	5.2247	5.2428	3.975	1.6169	2.6819
27	21	1	177.5	1	86.60176322	-3.9655	-2.5648	-4.7871	-1.894	-0.71656	1.7354	-2.8703	-1.0986	-1.3672	-2.1321	-2.8204

Average individual participant power related asymmetry data.

						Mean RFD BAI	Eccentric Deceleration Peak RFD BAI	Concentric Acceleration Peak RFD BAI	Time to Peak (s)		
Subject ID	Age	Sex	Height	Handedness	Subject mass (kg)	MAX	MAX	MAX	Max Right	Max Left	Max Difference
1	21	1	178.5	1	91.94480811	-8.78199	-1.91512	2.95123	0.84667	0.83667	0.01
2	22	1	177.625	1	123.730785	3.7208	5.45372	-24.5555	0.56667	0.56333	0.00334
3	20	2	159.25	1	58.37665953	1.27168	5.57565	3.03392	1.2167	1.0733	0.1434
4	22	1	182	1	78.49930326	-3.63466	6.38443	18.6671	0.76667	0.76333	0.00334
5	21	2	162.25	1	58.79977041	0.313532	5.42628	-7.56932	0.92333	0.78	0.14333
6	27	1	177.875	1	88.33157532	0.11311	6.56445	-16.9499	0.73667	0.73	0.00667
7	19	2	164.5	1	67.96519493	7.13998	-8.4066	5.99511	0.77333	0.76333	0.01
8	20	1	177.875	1	68.79658227	10.7626	8.54776	-8.29235	1.2633	1.5267	-0.2634
9	21	2	169.875	1	83.34941179	-14.8631	4.79935	-3.02925	1.1167	1.0767	0.04
10	23	1	175	1	72.00770794	4.7847	-6.91817	-21.3994	0.83	0.82	0.01
11	21	1	184.875	2	77.3807735	-24.8336	-1.8016	16.8484	1.4633	0.88667	0.57663
12	20	2	165.75	1	76.69015385	9.99009	0.80295	16.1918	1.15	1.16	-0.01
13	21	2	169.875	1	65.38181623	0.085242	10.4521	-16.0097	0.63667	0.63333	0.00334
14	21	1	183.875	1	79.94635721	-1.9734	-4.03025	12.2918	0.77333	0.76667	0.00666
15	22	1	175.375	1	82.77441101	-3.7851	3.69863	14.2357	0.69	0.68	0.01
16	21	1	164.375	1	74.94865545	2.4563	6.095	9.11882	1.04	1.04	0
17	19	2	165.25	1	76.4145082	-1.4458	8.18217	18.55	0.95333	0.96333	-0.01
18	24	1	178	2	74.15964806	-2.0077	-3.35016	-1.30047	0.85333	0.86333	-0.01
19	20	1	170	1	60.32110303	-4.8547	-10.3052	-7.05142	0.66	0.65667	0.00333
20	21	2	160.75	1	60.20799178	-2.1931	1.3374	-3.31145	0.93333	0.93333	0
21	26	1	175.5	1	96.00228634	6.34787	10.446	16.5131	0.84	0.84	0
22	21	1	173.375	1	91.27654932	-1.8255	9.25157	-10.3333	0.85667	0.85667	0
23	19	2	168.5	1	67.47045892	16.8371	-6.93223	1.21247	1.1	1.27	-0.17
24	20	1	185.1	1	76.73010861	7.50451	7.6081	-8.65689	0.68	0.66667	0.01333
25	22	2	159.3	1	44.57182923	4.6119	14.9439	12.1516	1.08	0.85333	0.22667
26	21	1	178.9	1	78.40407198	-0.80386	14.2623	12.8777	1.2267	1.2233	0.0034
27	21	1	177.5	1	86.60176322	-3.13952	3.44386	16.0984	1.3867	1.2533	0.1334