# Occupant Kinematics of Braced 5th Percentile Female and 50th Percentile Male Volunteers in Low-Speed Frontal and Frontal-Oblique Sled Tests

Hana Chan, Devon L. Albert, F. Scott Gayzik, Andrew R. Kemper

***Abstract*** Pre-crash braking and low-severity frontal crash events occur at low speeds and over long durations, giving occupants enough time to potentially brace prior to impact. Active human body models can capture the effects of muscle activation on occupant response during these low-severity events, but must be validated with relevant volunteer data. The purposes of this study were to quantify the occupant kinematic responses of braced 5th percentile female and 50th percentile male volunteers in low-speed frontal and frontal-oblique sled tests, and to compare to matched relaxed tests. Six 5th percentile female and six 50th percentile male volunteers experienced multiple low-speed frontal and frontal-oblique sled tests consisting of two pulse severities (1 g and 2.5 g) and two muscle conditions per pulse severity (relaxed and braced). The volunteers' kinematic responses were quantified using a 3D Vicon motion capture system. Forward, lateral, and vertical excursions were compared between demographic groups and muscle conditions. Minimal kinematic differences were observed between females and males for the braced tests. Pre-impact bracing resulted in decreased kinematic responses for all volunteers compared to the relaxed tests.

***Keywords*** Autonomous braking, biomechanics, muscle activation, pre-crash event, pre-impact bracing

## I. INTRODUCTION

As crash avoidance technologies like autonomous emergency braking (AEB) become more prevalent in new vehicles, it is increasingly necessary to study occupant responses during these scenarios [1-2]. The low speed and long duration of pre-crash braking and low-severity crash events provide sufficient time for muscle activation to affect occupant response [3-4]. In particular, the long duration of these events give occupants ample time to react and potentially brace prior to an impending crash [5]. Previous studies indicate that bracing against the steering wheel prior to an impending crash is a common real world reaction or pre-crash manoeuvre [5]. Compared to other impact directions, drivers may be more likely to react or engage in pre-impact bracing prior to frontal crashes in response to AEB systems activating, as these systems were designed to function primarily during frontal crashes [1]. Real world crash reports indicate that only a small portion of frontal crashes occur in a full-frontal loading direction, and that most typically occur in a frontal-oblique or offset-frontal loading scenario [6-7].

Pre-impact bracing can have influential consequences on occupant response during low-severity pre-crash and subsequent crash events. Occupants may brace by extending their upper and lower extremities and pushing against the steering wheel, foot rest/pedals, and seat back [5, 8-9]. These variations in posture shift occupants away from an idealised seated (standard upright) position. Moving out of position can affect the efficacy of vehicle safety systems during a subsequent crash event, as current safety regulations and consumer safety ratings do not consider deviations from an idealised seated position [9-10]. Muscle tensing during a pre-crash event can also affect the kinematics and kinetics of occupants during a subsequent crash, especially during a low-severity impact [11-12]. Previous studies have observed that occupant posture and bracing levels (along with occupant mass and stature) are shown to be significant factors in affecting injury risk in frontal crashes [13-14].

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Anthropomorphic test devices (ATDs) are commonly used to evaluate occupant safety in vehicle crashes, but are primarily validated based on the responses of post-mortem human surrogates (PMHSs) during high-severity tests [15-18]. These surrogates inherently lack muscle activity and may not be able to capture the live human response, especially during low-severity events. The ability to account for the influence of active musculature on occupant response during pre-crash and low-severity crash events is increasingly important. As such, computational active human body models (HBMs) can be used to represent the response of live occupants more accurately during these scenarios [4, 19-30]. Current versions of these models remain limited however, as they are typically validated with 50$^{th}$ percentile male volunteer test data, which is not representative of all occupant demographic groups [4, 19-23, 26-27, 30]. In the few instances where other demographic groups, e.g., 5$^{th}$ percentile females, are considered, the data used for model development and validation is typically scaled 50$^{th}$ percentile male volunteer data [24, 28]. The 50$^{th}$ percentile male and 5$^{th}$ percentile female demographic groups are the standard adult occupant populations most frequently used in current frontal impact vehicle safety standards [10]. Consequently, occupant safety evaluations with physical surrogates, e.g., the Hybrid III and Test Device for Human Occupant Restraint (THOR) ATDs, and computational models, e.g., the Global Human Body Models Consortium (GHBMC) and Total Human Model for Safety (THUMS) HBMs, focus on these demographic groups. However, these physical and computational tools must be validated with appropriate biomechanical data.

Validation data for low-severity events are available in the form of occupant kinematics of relaxed and braced male volunteers, but there is generally less female volunteer data available [11, 31-36]. This precludes the ability to make direct comparisons between demographic groups or properly validate female active HBMs. In particular, there is a scarcity of available small female volunteer data. It is especially important to consider small females when designing tools to assess occupant safety because they represent the smallest adult occupants, making them a vulnerable occupant population with increased injury risks in vehicle crashes [37-40]. Therefore, the objectives of this study were to quantify the occupant kinematic responses of braced 5$^{th}$ percentile female and 50$^{th}$ percentile male volunteers during low-speed frontal and frontal-oblique sled tests, and to compare to previously published data from matched relaxed tests.

## II. METHODS

Six female and six male volunteers (23.7 ± 2.3 years old), approximately 5$^{th}$ percentile (156.7 ± 6.1 cm, 50.0 ± 2.4 kg) and 50$^{th}$ percentile (175.9 ± 2.1 cm, 76.0 ± 3.3 kg), respectively, in height and weight, participated in this study [41]. A complete description of the volunteers' demographic and anthropometric information was previously published [41]. Volunteer testing was approved by the Virginia Tech Institutional Review Board, USA, and each volunteer signed an informed consent form at the start of each test day. All volunteers wore a cotton sleeveless shirt, tight-fitting cotton shorts, and military spec shoes that were provided by the research group.

Each volunteer experienced multiple low-speed sled tests on two separate days (7-10 days apart). On each day, the volunteers experienced either pure frontal (principal direction of force (PDOF) = 0°) or frontal-oblique (PDOF = 330°) sled tests at two pulse severities (1 g and 2.5 g) with two muscle conditions (relaxed and braced) per pulse severity (Fig. 1-3). The sled tests were conducted in the same order on each test day: 1 g relaxed ($\Delta v$ = 9.47 kph), 1 g braced ($\Delta v$ = 9.39 kph), 2.5 g relaxed ($\Delta v$ = 5.33 kph), and 2.5 g braced ($\Delta v$ = 5.09 kph). Half the volunteers experienced frontal tests on their first test day, and half the volunteers experienced frontal-oblique tests on their first test day. All volunteers experienced both test orientations between their two test visits. The 1 g pulse was designed to simulate an autonomous braking event and the 2.5 g pulse was designed to simulate a low severity frontal crash (Fig. 3) [3, 42-45].

For the relaxed tests, the volunteers were unaware of the test start but were told that the pulse would be randomly triggered within the next few minutes. They were instructed to sit in a relaxed manner, face forward, and focus on a monitor playing a television show or movie. When the volunteers appeared relaxed, relatively still, and focused on the monitor, the pulse was triggered out of sight. For the braced tests, the volunteers were aware of the test start and were given a countdown ("3..2..1..Go"). They were instructed to sit in a manner similar to the relaxed tests at first and to begin bracing two seconds prior to the test start by pushing with maximum effort onto the test buck using their arms, legs, and torso (Fig. 1-2). For both the relaxed and braced

tests, an oscilloscope connected to a surface electromyography (EMG) sensor on the volunteers' right triceps brachii muscle was used to monitor muscle activity levels in real time. This was done to confirm that the volunteers were not actively bracing before the start of the sled pulse for the relaxed tests, and that the volunteers were actively bracing before the start of the sled pulse for the braced tests. The volunteers' initial joint angles and reaction forces from the relaxed and braced tests were previously published and showed clear differences between the two muscle conditions [46]. Specifically, the braced volunteers exhibited greater initial joint angles and reaction forces at the test start compared to the relaxed volunteers.

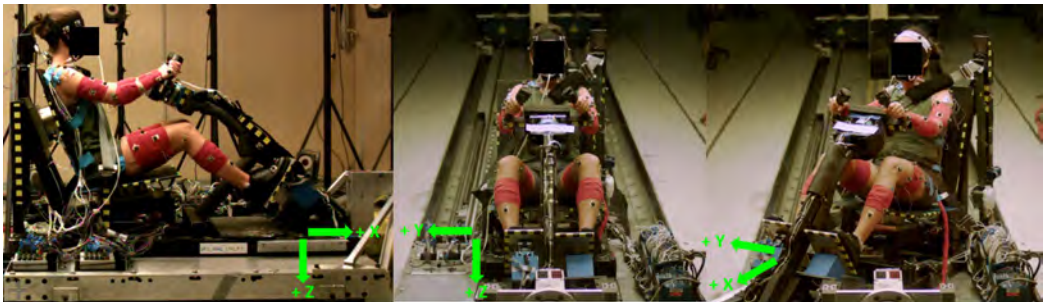


Fig. 1. Braced female volunteers at the test start in the frontal (left and centre) and frontal-oblique (right) test orientations. Note: The local coordinate system is aligned with the test buck for both test orientations.

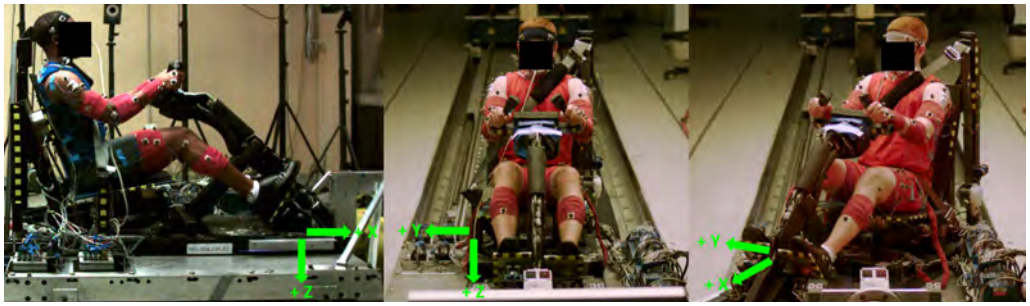


Fig. 2. Braced male volunteers at the test start in the frontal (left and centre) and frontal-oblique (right) test orientations. Note: The local coordinate system is aligned with the test buck for both test orientations.

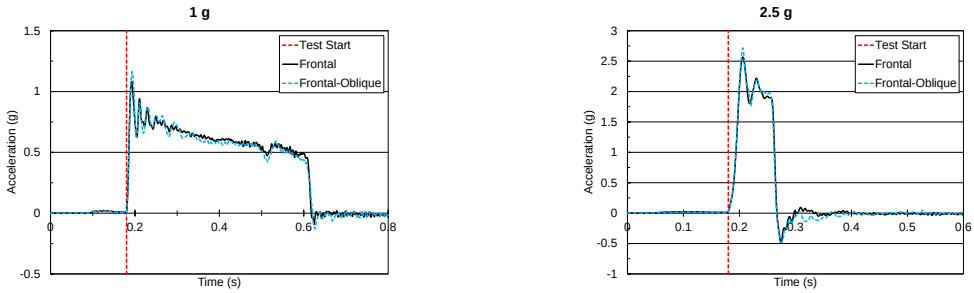


Fig. 3. Time histories of average sled pulse accelerations, aligned with the PDOF, for the braced 1 g (left) and braced 2.5 g (right) pulse severities in the frontal (solid black) and frontal-oblique (dashed blue) test orientations.

The sled tests were performed using a custom rigid test buck and mini-sled accelerated by a pneumatic piston. The test buck, originally designed for 50$^{th}$ percentile males, was modified for 5$^{th}$ percentile females by installing rigid aluminum spacers at each volunteer-test buck interface including the seat back, seat pan, steering column, and left and right foot pedals. These modifications positioned the reaction surfaces to accommodate the anthropometry of 5$^{th}$ percentile females and to maintain consistent initial joint angles between female and male volunteers. Similar initial joint angles were observed between the volunteer demographic groups for both muscle conditions [46]. A detailed description of the test buck and its dimensions were previously published [46]. A standard 3 kN load-limiting United States driver-side three-point seatbelt from a Toyota Camry that fits model years 2007-2011 was used for all sled tests, and the slack in the seatbelt was manually removed prior to the test start.

A Vicon motion capture system (Vicon Motion Systems, Oxford, United Kingdom) was used to quantify the

3D coordinates of the volunteers and the test buck during each sled test (1000 Hz sampling rate). Retro-reflective markers were attached to the test buck and to the volunteers using a custom marker set that included key anatomical locations and ancillary segment markers (Fig. 1-2). Specific regions of interest included the centre of gravity of the head (head CG), seventh cervical vertebra (C7), acromia (shoulders), lateral humeral epicondyles (elbows), greater trochanters (hips), and lateral femoral epicondyles (knees) [46]. Certain markers, e.g., left acromion, left and right greater trochanter, were sometimes removed from the volunteers prior to the sled tests to prevent contact between the markers and the shoulder and lap belts. Some markers were also obstructed from the field of view during some sled tests. Any missing markers were reconstructed using static capture data, collected prior to sled testing, and rigid body mechanics.

Marker trajectories relative to the test buck were calculated by subtracting test buck motion. Marker trajectories were also converted to the local test buck coordinate system, aligned with the orientation of the test buck. Forward (+ x) excursions of the specific regions of interest were calculated from corresponding marker trajectory data relative to initial marker positions at the start of each sled test. Lateral (+ y right) and vertical (+ z down) excursions of the specific regions of interest were also calculated. All marker trajectory data were cut at the time of peak forward excursion.

Kinematic data from the braced tests are presented in this study, and then compared to previously published kinematic data from matched relaxed tests [41]. Kinematic differences between test days were observed for some relaxed tests [41]. As such, volunteer kinematic responses from the braced tests were first compared between test days to evaluate any potential differences. These analyses were performed to determine if volunteers who experienced a particular test condition on their first day exhibited a different response than volunteers who experienced the same test condition on their second day. The volunteers were exposed to several sled tests over two test days and it was possible that they could have developed a habituated or learned response due to multiple exposures, in which case, data for the same test condition from separate test days could not be combined into one group. To determine if any test day differences had occurred, the average peak forward, lateral, and vertical excursions of all regions of interest were compared between volunteers who experienced a particular braced test condition on their first test day and volunteers who experienced the same braced test condition on their second test day.

Volunteer kinematic responses from the braced tests were next compared between females and males after accounting for any test day differences to determine if kinematics were affected by demographic group. If a meaningful difference in peak forward, lateral, or vertical excursions was observed between test days for a specific region of interest within a particular braced test condition, only volunteers who experienced the braced test condition on their first test day were included in subsequent comparisons for that particular region of interest. Average peak forward, lateral, and vertical excursions of all regions of interest were compared between demographic groups.

Finally, volunteer kinematic responses were compared between the relaxed and braced tests to determine if kinematics were affected by muscle condition. Comparisons between muscle conditions were limited to only first test day data because potential test day effects were observed for the relaxed tests. Average peak forward, lateral, and vertical excursions of all regions of interest were compared between muscle conditions for both females and males.

The sample size of this study precluded the ability to perform confirmatory statistical analyses to assess significant differences between comparison groups. As with previous analyses of the relaxed kinematic data, differences in peak excursions in this study were deemed meaningful when both of the following criteria were met: the magnitude of the difference was equal to or greater than two centimetres, and the average ± the standard deviation from one comparison group did not overlap with the average from the other comparison group [41]. These criteria were applied to compare average peak forward, lateral, and vertical excursions between test day groups, demographic groups, and muscle conditions. These criteria were selected to analyze previously published relaxed kinematics, and were developed by conducting post-hoc power analyses using results from previous studies with similar test conditions, volunteer inclusion criteria, and/or peak forward excursions [11, 41, 47]. In these studies, approximately two centimetres of forward excursion corresponded to the minimum difference for significance between different test conditions [11, 47].

## III. RESULTS

### *Test Day Differences*

There were generally negligible or little differences in C7, shoulder, elbow, hip, and knee forward, lateral, and vertical excursions between volunteers who experienced the same braced test condition on different test days (Δ = -1.72 to 2.46 cm, Fig. A1-A4). Positive differences indicate that first day excursions were greater in magnitude than second day excursions.

For both females and males, meaningful differences were present in some head CG excursions between volunteers who experienced the same braced test on their first or second test day (Fig. A1-A4). Test day differences were observed in peak forward head CG excursions for females in the frontal-oblique 1 g braced test condition (Δ = 3.69 cm, Fig. A3) and for males in the frontal 1 g braced test condition (Δ = 3.58 cm, Fig. A1). The females and males who experienced these braced test conditions on their first day exhibited greater forward head movement compared to females and males who experienced the same braced test conditions on their second day (Fig. A1, A3).

Meaningful test day differences were observed in vertical head CG excursions (at the time of peak forward excursions) for males in the frontal 2.5 g (Δ = -2.11 cm), frontal-oblique 1 g (Δ = 2.36 cm), and frontal-oblique 2.5 g (Δ = 3.03 cm) braced test conditions (Fig. A2-A4). The males who experienced the frontal 2.5 g braced test on their second day exhibited greater downward head movement compared to volunteers who experienced the same braced test on their first day (Fig. A2). In contrast, the males who experienced the frontal-oblique braced tests on their first day exhibited greater downward head movement compared to volunteers who experienced the same braced tests on their second day (Fig. A3-A4).

### *Demographic Group Differences*

Meaningful differences in forward, lateral, or vertical excursions were generally not observed between females and males for the braced tests (Δ = -1.89 to 1.54 cm, Fig. 4-5, Fig. A1-A4). Positive differences indicate that the males' excursions were greater in magnitude than the females' excursions. Test day differences were observed in head CG excursions for several of the braced test conditions, so subsequent head CG excursion comparisons for all braced test conditions between females and males were limited to volunteers who experienced those tests on their first day. Meaningful differences between demographic groups were observed in peak forward head CG excursions for the frontal 2.5 g braced test condition (Δ = 2.41 cm, Fig. 4, Fig. A2), where males exhibited greater forward head movement compared to females, and for the frontal-oblique 1 g braced test condition (Δ = -2.39 cm, Fig. 5, Fig. A3), where females exhibited greater forward head movement compared to males.

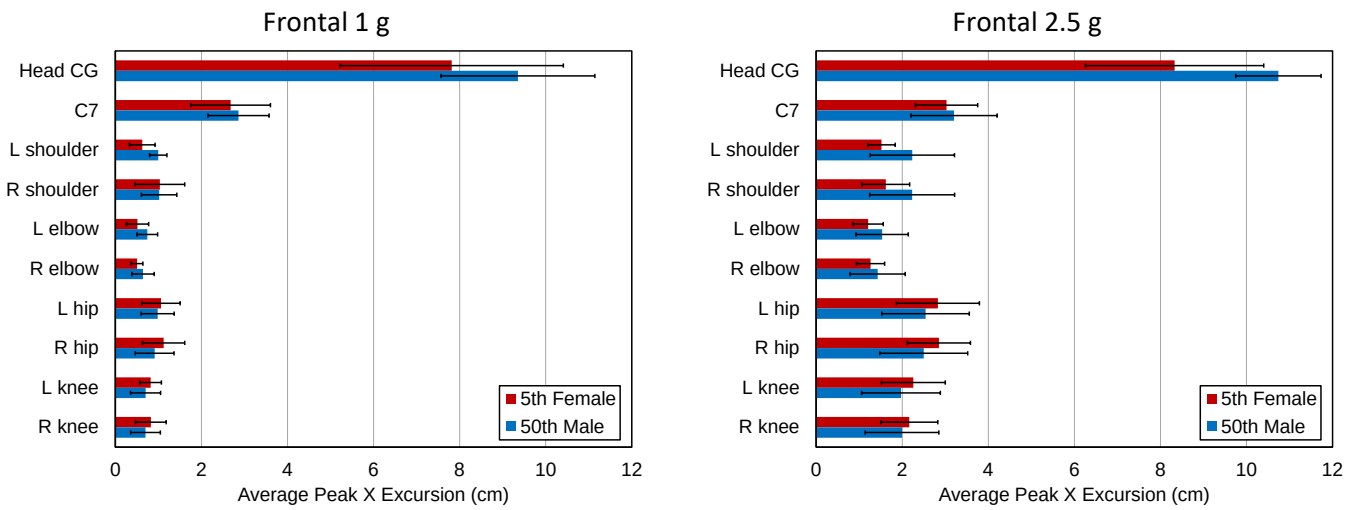


Fig. 4. Female and male average (± standard deviation) peak forward excursions for the frontal braced tests. Head CG excursions are limited to first day data only to account for observed test day differences. The remaining anatomical location excursions include both first and second day data.

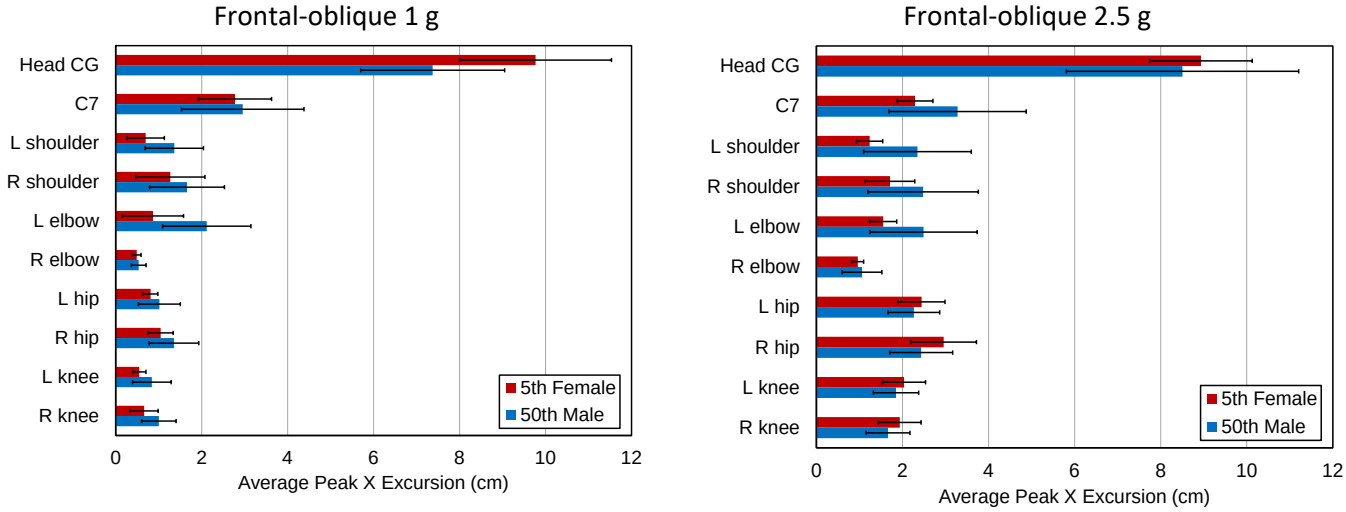


Fig. 5. Female and male average (± standard deviation) peak forward excursions for the frontal-oblique braced tests. Head CG excursions are limited to first day data only to account for observed test day differences. The remaining anatomical location excursions include both first and second day data.

### *Muscle Condition Differences*

The volunteers generally had smaller excursions for the braced tests compared to the relaxed tests across test conditions and demographic groups (Fig. 6-7, A5-A8). Test day differences were observed for some relaxed tests, so comparisons between relaxed and braced tests were limited to first day data only for all anatomical locations and for both demographic groups, in order to maintain consistent sample sizes between muscle conditions [41]. Positive differences indicate that excursions from the relaxed tests were greater in magnitude than excursions from the braced tests.

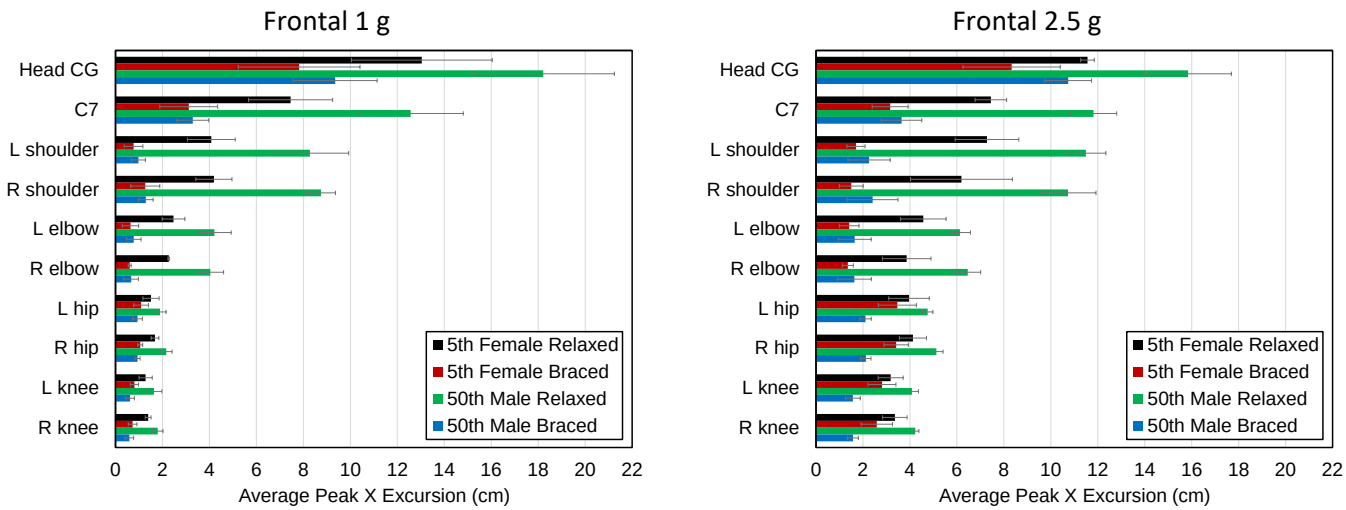


Fig. 6. Female and male average (± standard deviation) peak forward excursions for the relaxed and braced tests. Excursions are limited to first day data only for all groups.

For the frontal tests, meaningful differences between muscle conditions were generally limited to peak forward excursions for both females and males. In general, the upper bodies of the relaxed volunteers exhibited greater forward movement compared to the braced volunteers in the frontal orientation (Fig. 6, A5-A6). Meaningful differences were observed between muscle conditions in the female and male volunteers' peak forward head CG, C7, and left and right shoulder excursions for all frontal tests (Δ = 2.92 – 9.27 cm, Fig. 6, Fig. A5-A6). Meaningful differences were also observed between muscle conditions in the volunteers' peak forward left and right elbow excursions for females in the frontal 2.5 g test condition and for males in both frontal test conditions (Δ = 2.51 – 4.83 cm, Fig. 6, Fig. A5-A6). The lower bodies of the relaxed volunteers mostly exhibited similar forward movement compared to the braced volunteers in the frontal orientation (Fig. 6, A5-A6). There

was generally minimal difference in peak forward hip and knee excursions between relaxed and braced volunteers for all frontal tests and both demographic groups (Δ = 2.51 – 3.00 cm), except for males in the frontal 2.5 g test condition (Fig. 6, A5-A6). The relaxed volunteers and braced volunteers mostly exhibited similar overall lateral and vertical movement in the frontal orientation (Fig. A9-10). Meaningful differences were observed between muscle conditions in vertical left and right knee excursions (at the time of peak forward excursions) for males in the frontal 2.5 g test condition (Δ = 2.88 – 3.42 cm, Fig. A6, Fig. A10).

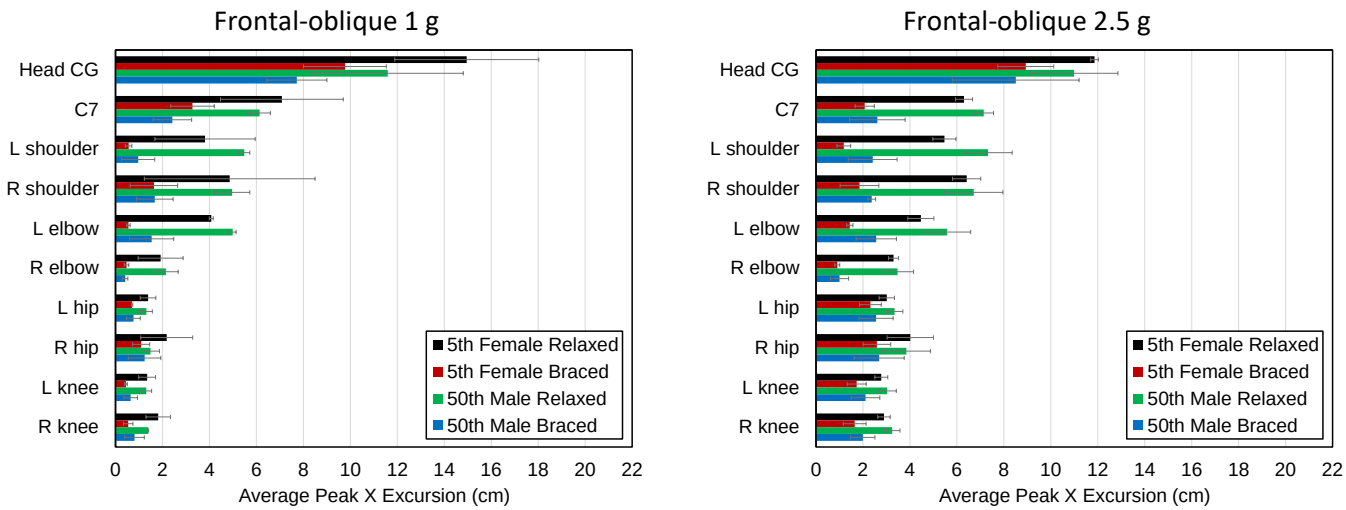


Fig. 7. Female and male average (± standard deviation) peak forward excursions for the relaxed and braced tests. Excursions are limited to first day data only for all groups.

For the frontal-oblique tests, meaningful differences between muscle conditions were generally present across forward, lateral, and vertical excursions for both females and males. Similar to the frontal tests, the relaxed volunteers mostly exhibited greater upper body forward movement and similar lower body movement compared to the braced volunteers in the frontal-oblique orientation (Fig. 7, A7-A8). Meaningful differences were observed between muscle conditions in the female and male volunteers' peak forward head CG, C7, left and right shoulder, and left elbow excursions for all frontal-oblique tests (Δ = 3.01 – 5.19 cm), except for male head CG excursions in the frontal-oblique 2.5 g test condition (Fig. 7, A7-A8). Meaningful differences were also observed between muscle conditions in the female and male volunteers' peak forward right elbow excursions for the frontal-oblique 2.5 g test condition (Δ = 2.40 – 2.47 cm, Fig. 7, Fig. A8). Across all frontal-oblique tests and both demographic groups, there was little difference in peak forward hip and knee excursions between relaxed and braced volunteers (Δ = 0.3 – 1.4 cm, Fig. 7, Fig. A7-A8).

The relaxed volunteers mostly exhibited greater upper body leftward movement, similar lower body leftward movement, and similar overall downward movement compared to the braced volunteers in the frontal-oblique orientation (Fig. A9-A10). In the lateral direction, meaningful differences between relaxed and braced volunteers were generally present in the females' and males' head CG, C7, left and right shoulder, and left and right elbow excursions for the frontal-oblique tests (Δ = 2.08 – 5.88 cm, Fig. A9). This was true except for lateral head CG excursions for females and males in the frontal-oblique 2.5 g test condition, lateral right shoulder excursions for females in the frontal-oblique 1 g test condition, and lateral left shoulder excursions for males in the frontal-oblique 2.5 g test condition. Minimal differences in lateral lower body excursions were observed between relaxed and braced volunteers, except for female knee excursions in the frontal-oblique 1 g and frontal-oblique 2.5 g (right only) test conditions (Δ = 2.50 – 3.44 cm, Fig. A9). In the vertical direction, meaningful differences between relaxed and braced volunteers were limited to right knee excursions for females and males in the frontal-oblique 2.5 g test condition, and head CG excursions for females in the frontal-oblique 1 g test conditions (Δ = 2.23 cm, Fig. A7-A8, A10).

## IV. DISCUSSION

The occupant kinematic responses of braced 5th percentile female and 50th percentile male volunteers during low-speed frontal and frontal-oblique sled tests were quantified and compared between demographic groups. The experimental design of this study also allowed direct comparisons to be made between braced tests and matched relaxed tests, which were previously published [41].

Meaningful differences in forward, lateral, or vertical excursions were generally not observed between volunteers who experienced a given braced test condition on their first day and those who experienced the same braced test condition on their second day, except for head excursions in some braced test conditions. For males in the frontal-oblique braced test conditions, the observed test day differences in vertical head excursions may be driven by an individual male volunteer who exhibited different pre-impact bracing mechanisms compared to other volunteers (Fig. A3-A4). The lack of test day differences in the braced tests are in contrast to the relaxed tests, where differences between test days were present in a considerable number of upper body locations and nearly all relaxed test conditions [41]. In instances where test day differences were present in the braced tests, greater forward head movement was mostly observed on the first day compared to the second day (except for males in the frontal 2.5 g braced test condition where the opposite trend was observed). This potential habituation between test days may have been the result of a learned response or subtle differences in pre-impact bracing between test days. In order to fully understand any possible changes in occupant response between test days, other subsets of data from this study, e.g., reaction forces and EMG, need to be fully analysed and evaluated to determine whether habituation between test days occurred. This is outside the scope of this manuscript but will be explored in future publications.

Both female and male volunteers generally had similar forward, lateral, and vertical excursions for the braced tests across all anatomical locations. These results are in contrast to the relaxed tests, where some differences between female and male excursions were observed. Males exhibited greater forward upper body movement compared to females for the frontal relaxed tests, but similar forward body movement for the frontal-oblique tests. Although males displaced forward more than females when relaxed in the frontal orientation, both demographic groups displaced forward comparably when braced (both orientations) or when relaxed in the frontal-oblique orientation. Similarities and/or differences in kinematic response between females and males during low-severity events have been evaluated in previous studies [33-34, 36, 48]. However, these studies focused on quantifying relaxed volunteer responses and rarely included a substantial number of small female volunteers, making direct comparisons to the braced volunteer responses in this study not as relevant.

The observed kinematic differences between females and males when relaxed and lack of these differences when braced is important to note when considering how both demographic group and muscle condition affect occupant response, especially during low-severity crash scenarios. The minimisation of kinematic differences between demographic groups when braced illustrates the need to consider varying states of muscle activation when utilizing active human body models to assess occupant response during low-severity crash scenarios. This also underscores the importance of validating these models with appropriate volunteer data, i.e., a range of demographic groups and a range of muscle conditions, in order to accurately predict occupant response and injury risk during pre-crash braking and low-severity frontal crash events.

Pre-impact bracing decreased volunteer forward, lateral, and vertical excursions compared to the relaxed tests across all anatomical locations. Overall, the braced volunteers exhibited less body movement than the relaxed volunteers across test conditions (both test orientations and pulse severities). This was true for both females and males, with a greater number of differences between muscle conditions observed in the head, neck, shoulders, and elbows compared to the hips and knees. The lack of meaningful differences between muscle conditions in the lower body may be because lower body excursions were already minimal for the relaxed tests [41]. The volunteers' lower bodies may also have been more constrained by the seatbelt and test buck interfaces. In comparison, the volunteers' upper bodies were not as constrained and the volunteers were able to extend their upper extremities more during bracing [46]. Kinematic differences between muscle conditions were present mostly in the forward direction for the frontal tests, but were present in all three directions for the frontal-oblique tests. This is likely because the volunteers exhibited both forward and lateral body movement during the frontal-oblique tests. The greatest number of differences between muscle conditions were observed for males in the frontal 2.5 g test condition, where differences were present across all anatomical locations including the lower body.

The observed decrease in kinematic response when braced during this study was expected and consistent with prior findings, as previous studies have shown that pre-impact bracing during low-severity sled tests reduces occupant kinematics in volunteers. Ejima et al. 2007 & 2008 tested male (174.0 ± 3.3 cm, 66.9 ± 4.3 kg) and female (162.0 ± 6.8 cm, 52.5 ± 8.2 kg) volunteers during frontal sled tests (0.2, 0.6, 0.8, and 1 g) and observed limited forward upper torso motion for the braced state compared to the relaxed state [32, 35]. Although some kinematic differences were observed between male and female volunteers in both muscle states, these demographic group differences could not be sufficiently supported or discussed due to the limited and unequal sample size (three/five males and two females). Ito et al. 2013 tested three male volunteers (170.3 ± 2.5 cm, 68.6 ± 5.9 kg) during frontal sled tests (0.7 g) and also observed constrained upper torso motion for the braced (tensed) state compared to the relaxed state [49]. For the braced state in these studies, the volunteers maintained their initial posture (similar to the relaxed state) and only tensed their muscles as opposed to extending their extremities and pushing into the steering column, foot pedals, and seat back with maximum effort. In the current study, the volunteers extended their extremities during pre-impact bracing, resulting in not only changes in initial reaction forces but also changes in initial posture (joint angles) [46]. As such, the braced volunteers began in a more rearward position compared to the relaxed volunteers. This, in combination with decreased excursions when braced, indicates that the overall final position, i.e., peak forward position, of the head, neck, and chest was considerably farther away from the steering wheel for the braced volunteers compared to the relaxed volunteers.

The female and male volunteers in this study may have moved forward more similarly when braced compared to when relaxed because they were fully aware prior to and during the braced tests. Reaction times and muscle mass may have played a more significant role in affecting muscle activation and occupant response when the volunteers were not aware of the test start during the relaxed tests. Given the low severity of the sled tests in this study, both the females and males may have braced more than was needed to modify their kinematic response between muscle conditions (they were specifically instructed to brace with maximum effort). As such, pre-impact bracing forces over a certain threshold could potentially result in similar diminished kinematics for low-severity events such as these. Similar diminished kinematics between female and male braced volunteers were observed for both the 1 g and 2.5 g pulse severities in this study. Beeman et al. 2011 tested 50$^{th}$ percentile male volunteers during frontal sled tests (2.5 g and 5 g) and observed that pre-impact bracing significantly reduced peak forward excursions (the volunteers were asked to brace in a similar manner to the current study) [11]. However, increasing pulse severity from 2.5 g to 5 g decreased the effects of pre-impact bracing on kinematic response. Specifically, head, shoulder, elbow, hip, and knee excursions decreased by 35-70% at the 2.5 g pulse severity, while head, shoulder, and elbow excursions decreased by 36-69% at the 5 g pulse severity. This trend suggests that although kinematic differences between demographic groups were not observed during the braced tests in the current study, they may emerge at higher severities where physical size, overall body mass, and muscle strength may play a more significant role in affecting occupant response.

Kinematic differences between muscle conditions are especially important to consider during low speed, long duration pre-crash braking and low-severity frontal crash events. These events occur over sufficient periods where reaction times, evasive manoeuvres, and bracing can potentially affect occupant muscle conditions and displacements prior to a crash. These factors could potentially move occupants out of position and affect their interactions with the vehicle interior and vehicle restraints [9]. This in turn could influence their potential injury risk as vehicle safety systems are designed and evaluated with human surrogates in an idealised driving position [13]. Consideration of these out of position scenarios is increasingly important as deployment of active safety systems like AEB become more prevalent in new vehicles. In particular, many active safety systems give a visual or auditory warning signal prior to an impending crash. When evaluating the efficacy of these active safety systems during the pre-crash phase, it is necessary to consider that occupants may react in a variety of ways in response to a warning signal, i.e., some may react more quickly or slower than others, some may brace prior to impact, etc.

A limitation of this study is that the volunteers were instructed to brace with maximum effort prior to the test start, which is not necessarily realistic of real world pre-impact bracing. It is more likely that occupants in real world pre-crash situations may brace in varying ways, i.e., different levels and combinations of upper and lower extremity bracing, prior to impact due to differences in reaction times, muscle mass, etc. It is expected that occupants in the real world are also more likely to respond in a manner that is in between the unaware

relaxed test conditions and aware braced test conditions from this study, which represent two extremes in a controlled scenario. Another limitation of this study is that the volunteers experienced each braced test condition only once. Prior exposure to pre-crash braking or low-severity crash events in the real world may also affect how an occupant may brace prior to impact, i.e., they could develop a learned or habituated response. Separate preliminary analyses from this study also indicate that pre-impact bracing forces can vary within and between volunteers, between females and males, and over the duration of the pre-crash phase. All of these factors could lead to a variety of pre-bracing mechanisms, which could potentially lead to changes in occupant kinematic and kinetic outcomes. Active HBMs can be used to explore the implications of different pre-impact bracing mechanisms on occupant response, if given the necessary range of pre-impact bracing volunteer data needed for proper validation. Differences in how pre-impact bracing affect occupant response will be evaluated using active human body models in future work. A final limitation of this study is that the comparisons between 5$^{th}$ percentile female and 50$^{th}$ percentile male volunteers were made without accounting for the difference in size (height and weight) between the two demographic groups. As such, both sex and size factors likely affect the demographic group differences presented in this study.

In addition to being used for active HBM development and validation, the kinematic response data from this study can also be used to develop and validate ATDs for use during low-severity frontal crash events. Current ATDs do not necessarily predict occupant response accurately at low severities because they are typically evaluated with PMHS data obtained from high-severity tests. PMHSs inherently lack muscle activity and may not be able to accurately capture the response of live occupants during low-severity events. This live response is especially important as low severities where muscle activation and reaction times may affect occupant response prior to and during impact. It is necessary for the kinematic response of ATDs to match that of live occupants in order for vehicle restraints to be effective at reducing injury risk. As crash avoidance technologies become more available in new vehicles, vehicle restraint effectiveness also needs to be thoroughly evaluated during low-severity scenarios, especially in the event of out of position occupants. As such, ATDs need to be developed and validated using volunteer response data from low-speed sled tests that simulate realistic low-severity pre-crash and frontal crash events. Future work will include evaluating the kinematic response of current ATDs in matched sled tests and comparing to volunteer data, in order to help with ongoing improvement and evaluation of ATD design and use.

Finally, a necessary component to wholly understanding pre-impact bracing and its effect on occupant response is quantifying reaction forces and EMG from volunteers during low-speed sled tests. The kinematic data presented here is part of a larger data set collected during this low-speed volunteer sled testing study. Future publications will present and discuss the methods, results, and implications of reaction force and EMG data from relaxed and braced volunteers (both females and males).

## V. CONCLUSIONS

Pre-impact bracing decreased occupant kinematics for 5$^{th}$ percentile female and 50$^{th}$ percentile male volunteers during low-speed frontal and frontal-oblique sled tests that were similar to pre-crash braking and low-severity crash events. When braced, female and male volunteers generally exhibited similar kinematic responses across all anatomical locations.

This study provides novel kinematic response data from small female and mid-size male volunteers that can be used to further develop and validate active human body models for a wider demographic range of occupants in varying muscle conditions. These models will aid in understanding occupant response, injury risk, and vehicle restraint effectiveness during pre-crash braking and low-severity frontal crash events, particularly in situations where active safety systems may deploy.

## VI. ACKNOWLEDGEMENTS

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# VIII. APPENDIX

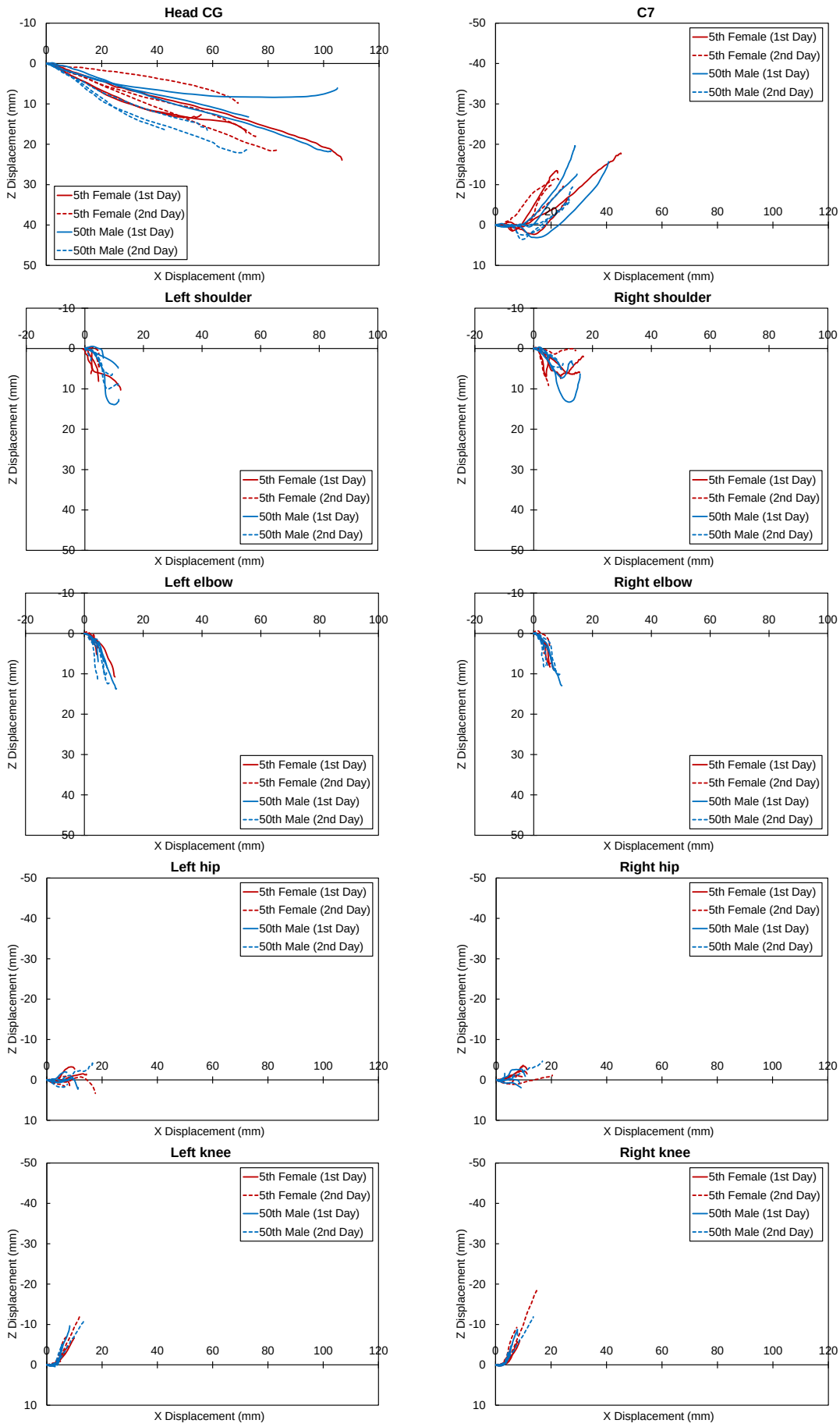


Fig. A1. Female and male sagittal plane excursions for the frontal 1 g braced tests.

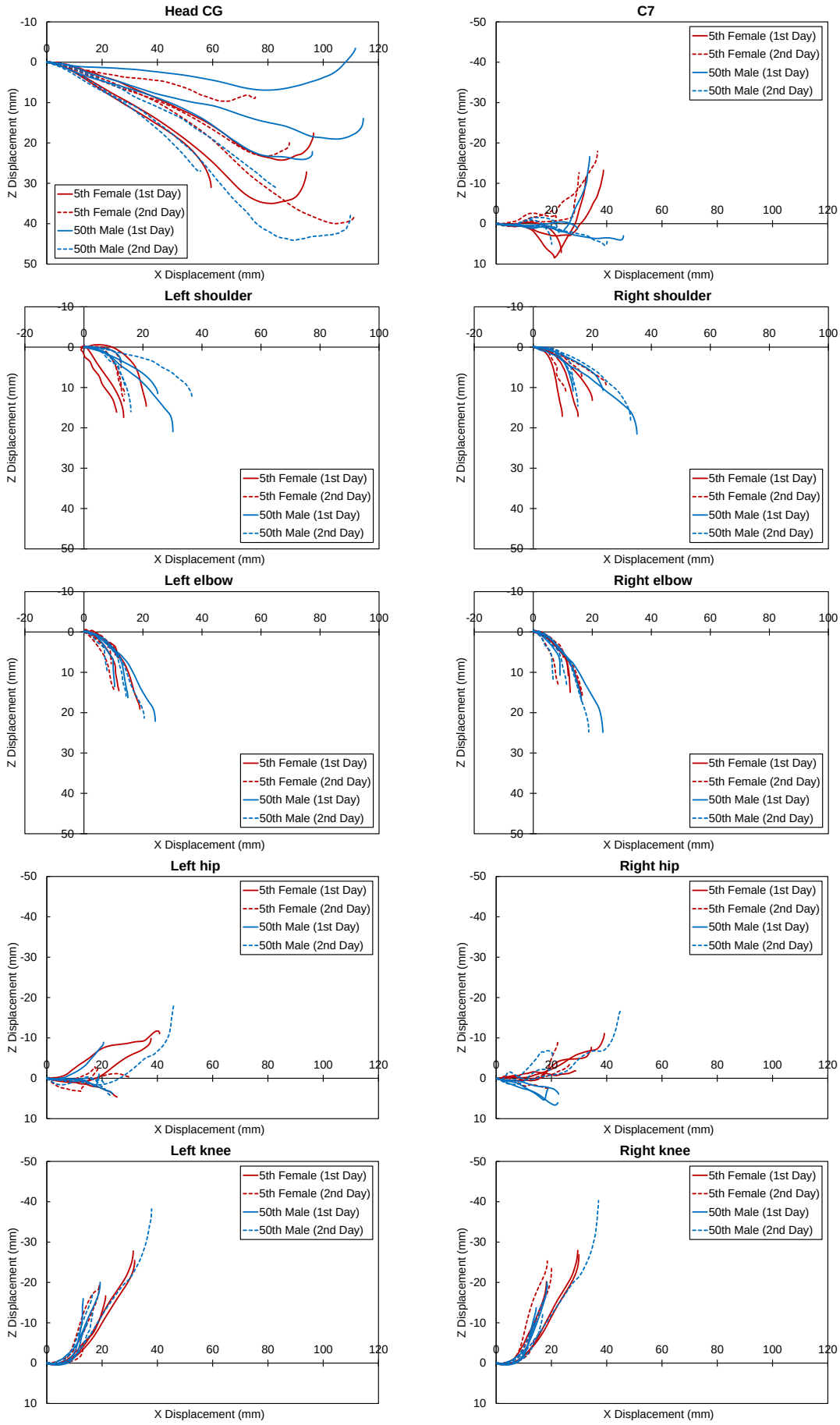


Fig. A2. Female and male sagittal plane excursions for the frontal 2.5 g braced tests.

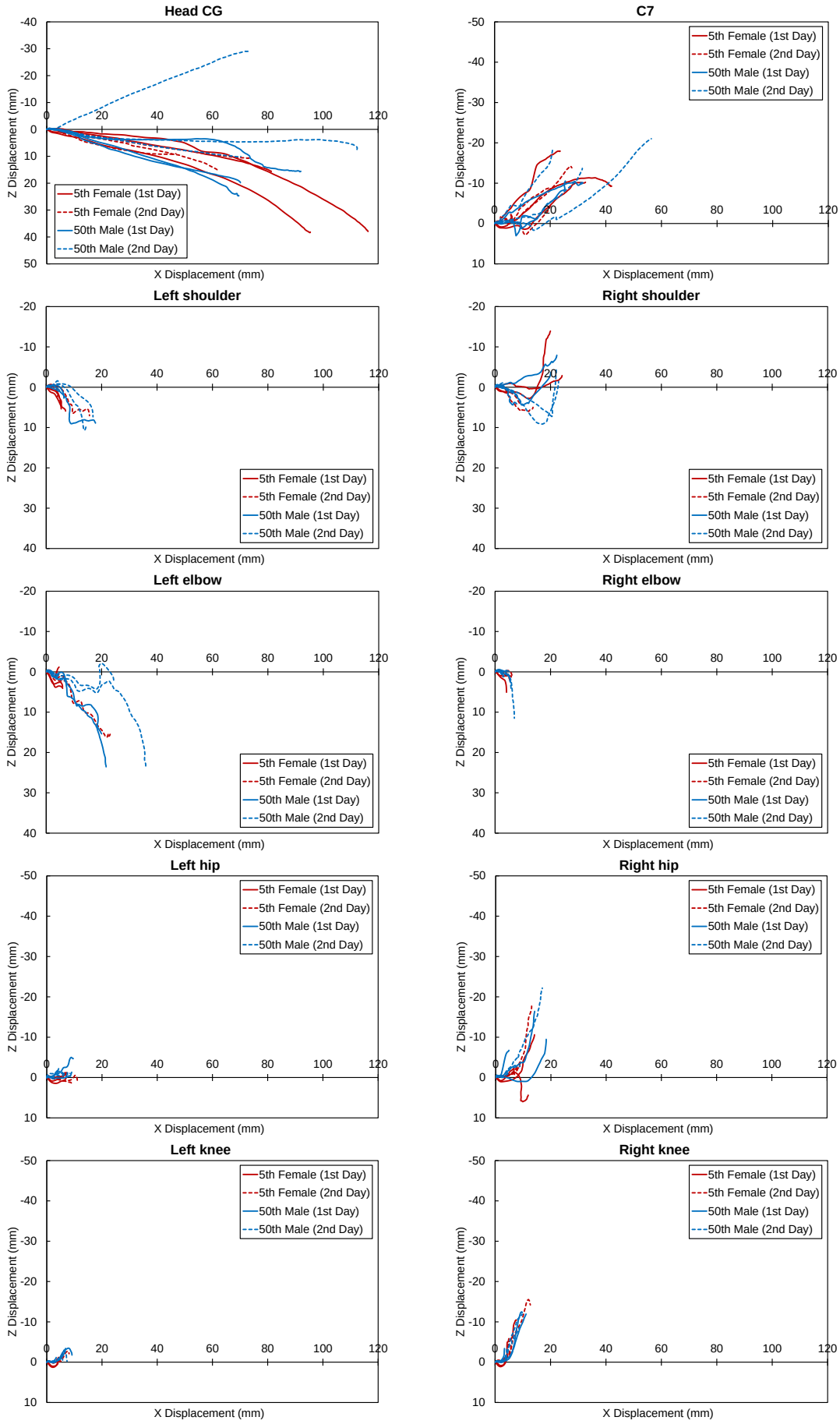


Fig. A3. Female and male sagittal plane excursions for the frontal-oblique 1 g braced tests.

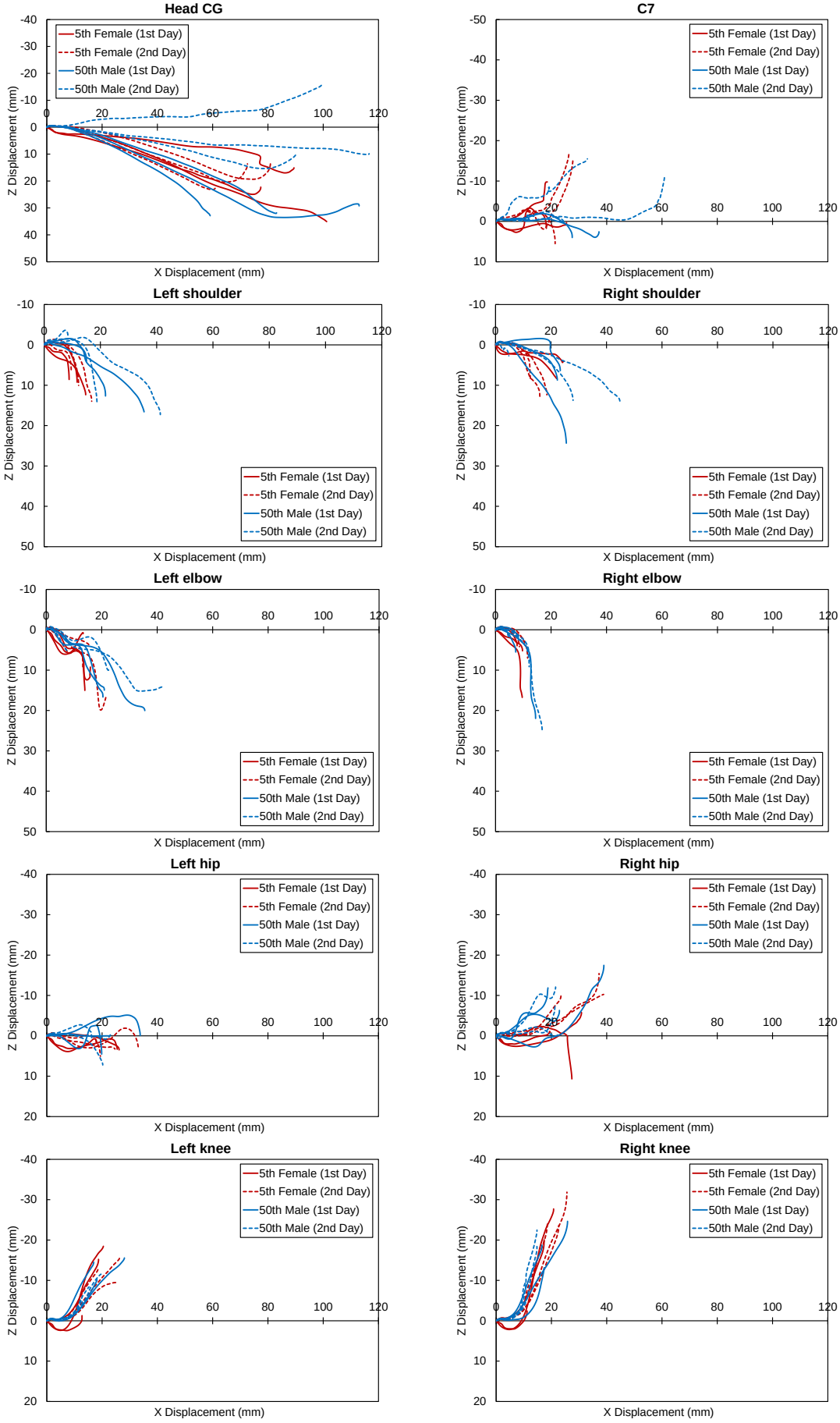


Fig. A4. Female and male sagittal plane excursions for the frontal-oblique 2.5 g braced tests.

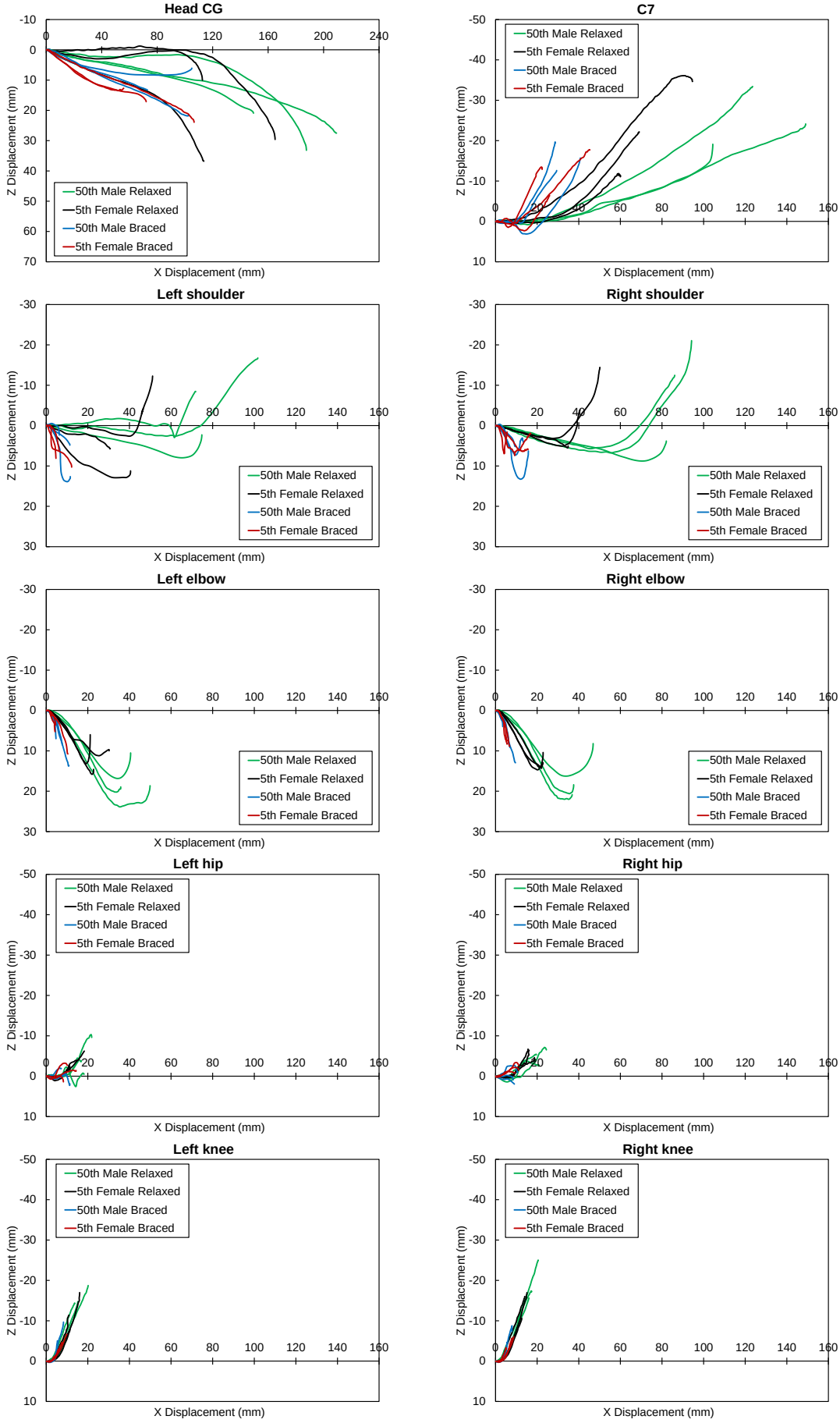


Fig. A5. Relaxed and braced sagittal plane excursions for the frontal 1 g tests (first day data only).

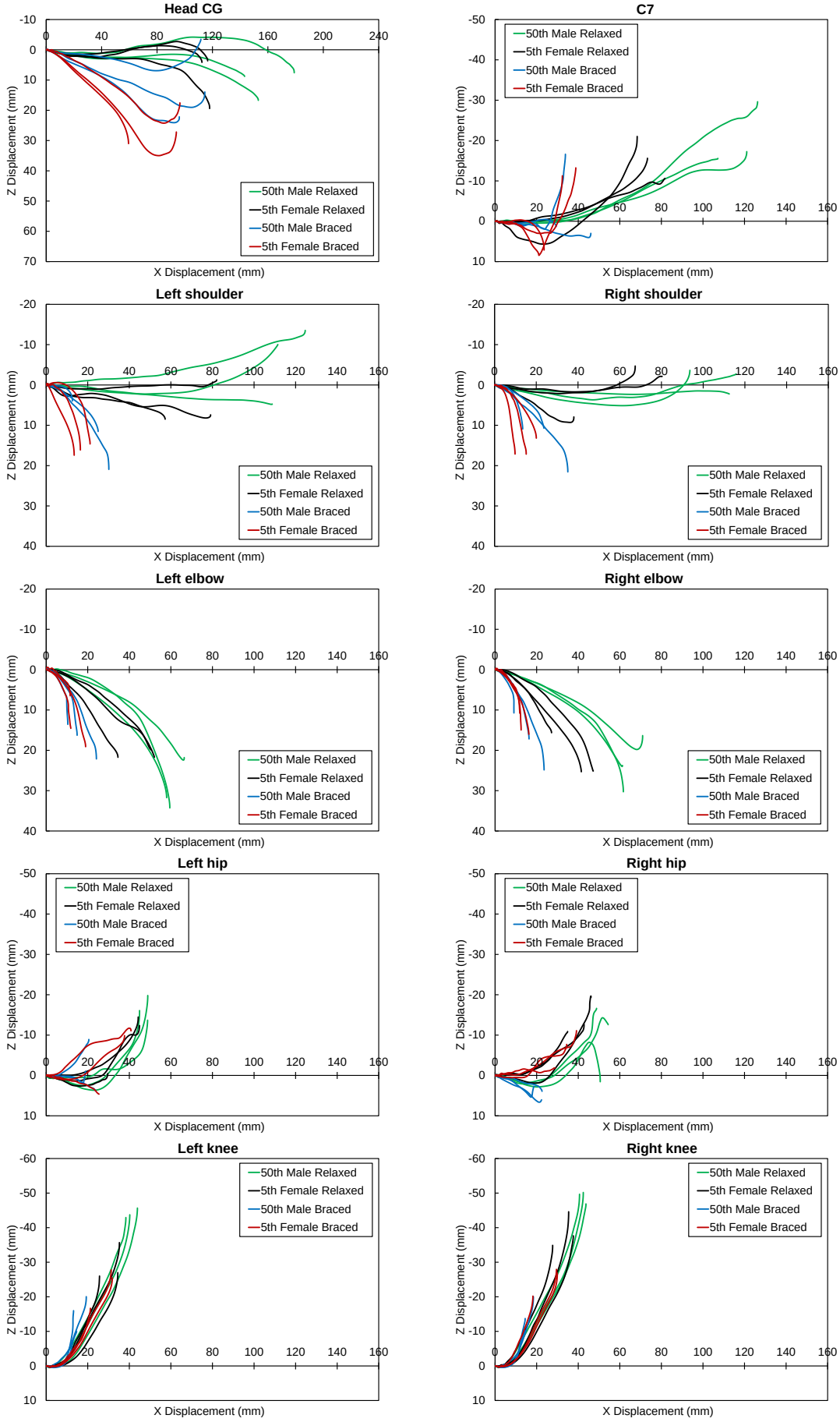


Fig. A6. Relaxed and braced sagittal plane excursions for the frontal 2.5 g tests (first day data only).

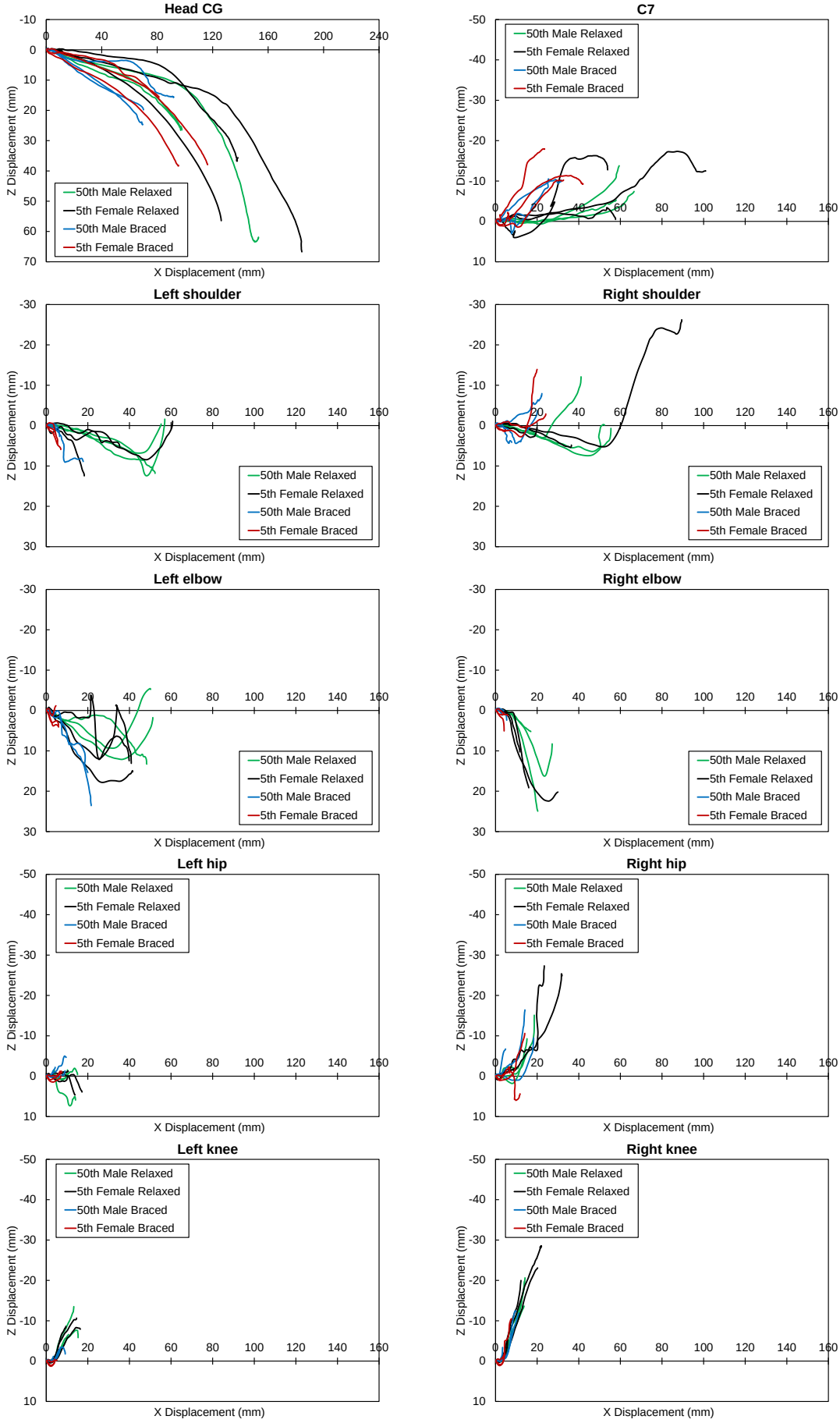


Fig. A7. Relaxed and braced sagittal plane excursions for the frontal-oblique 1 g tests (first day data only).

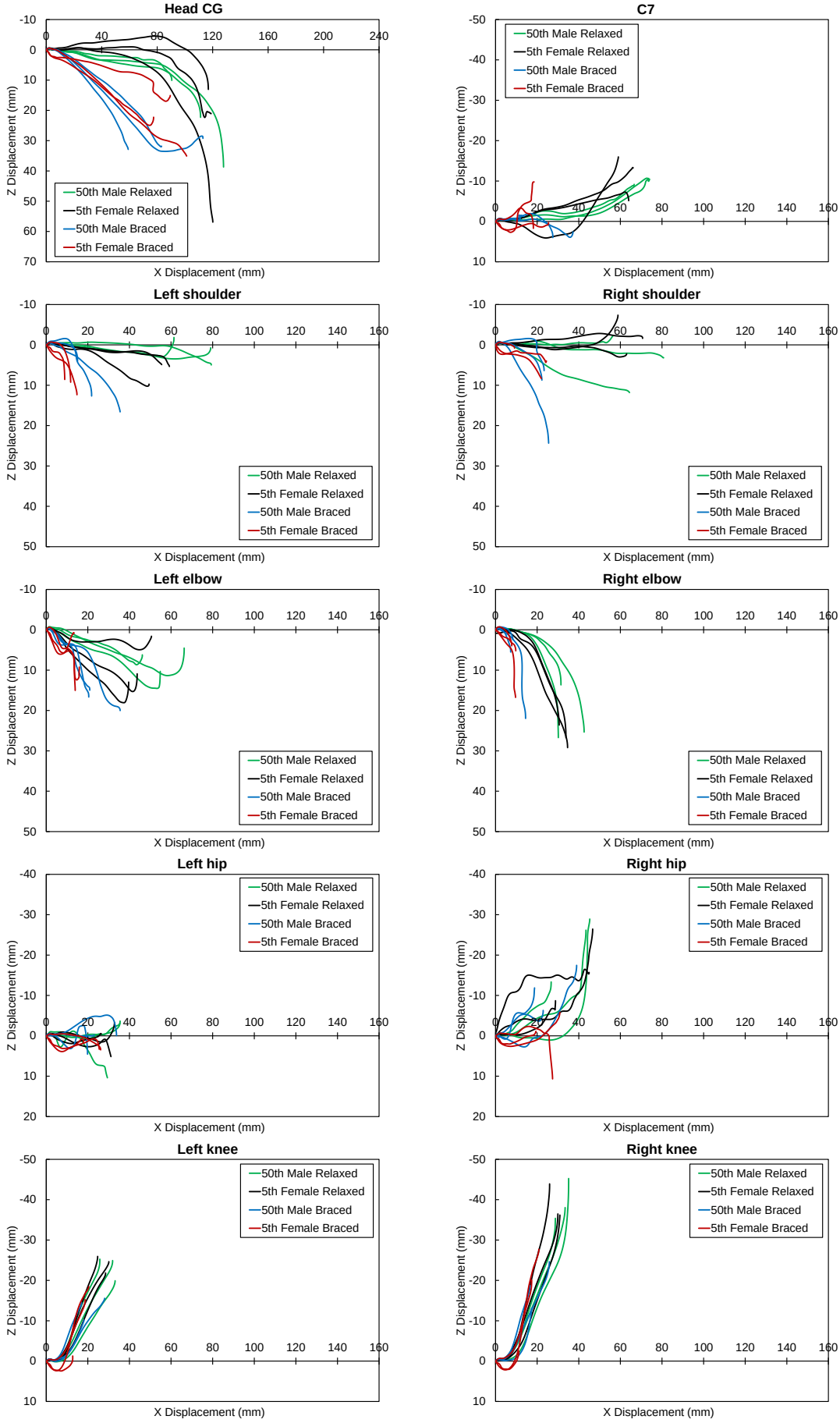


Fig. A8. Relaxed and braced sagittal plane excursions for the frontal-oblique 2.5 g tests (first day data only).

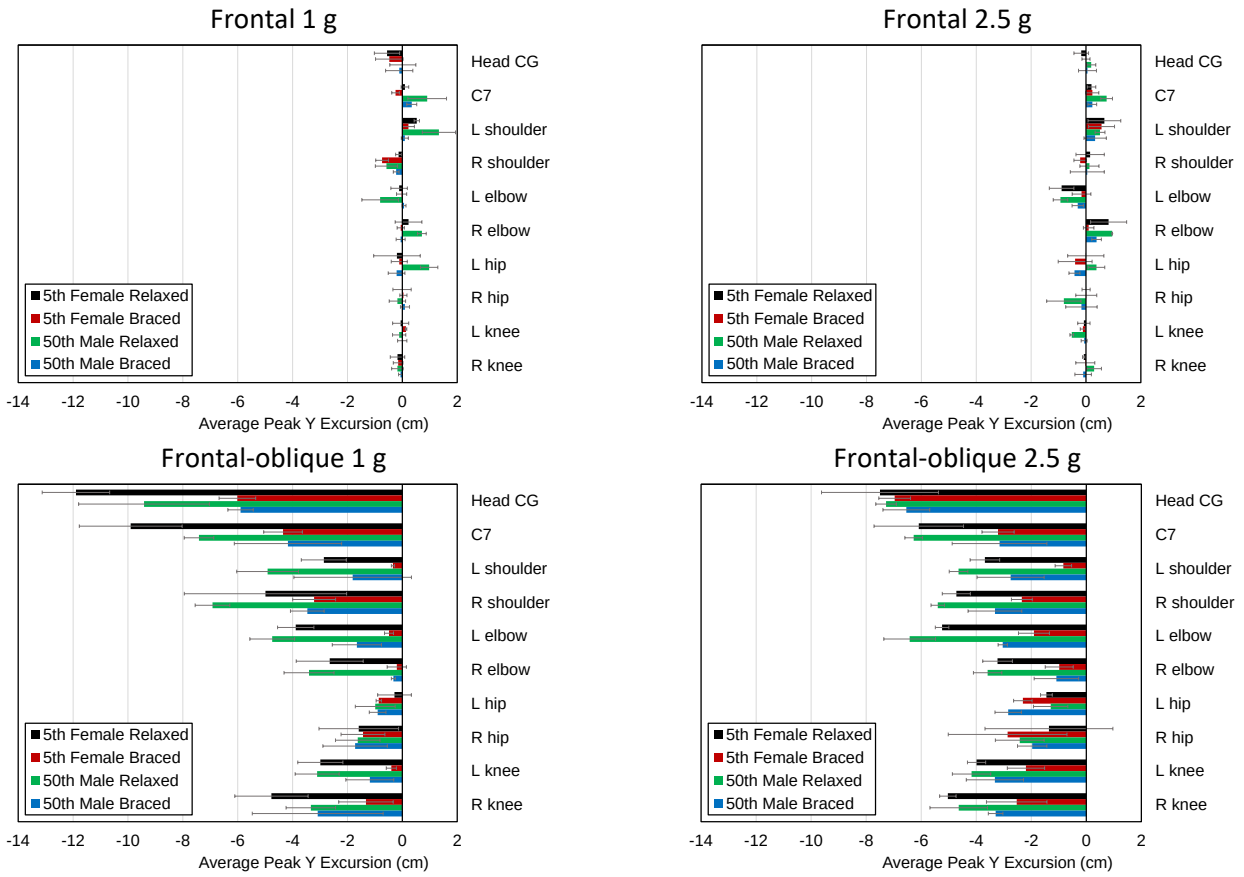


Fig. A9. Female and male average (± standard deviation) peak lateral excursions for the relaxed and braced tests. Excursions are limited to first day data only for all groups.

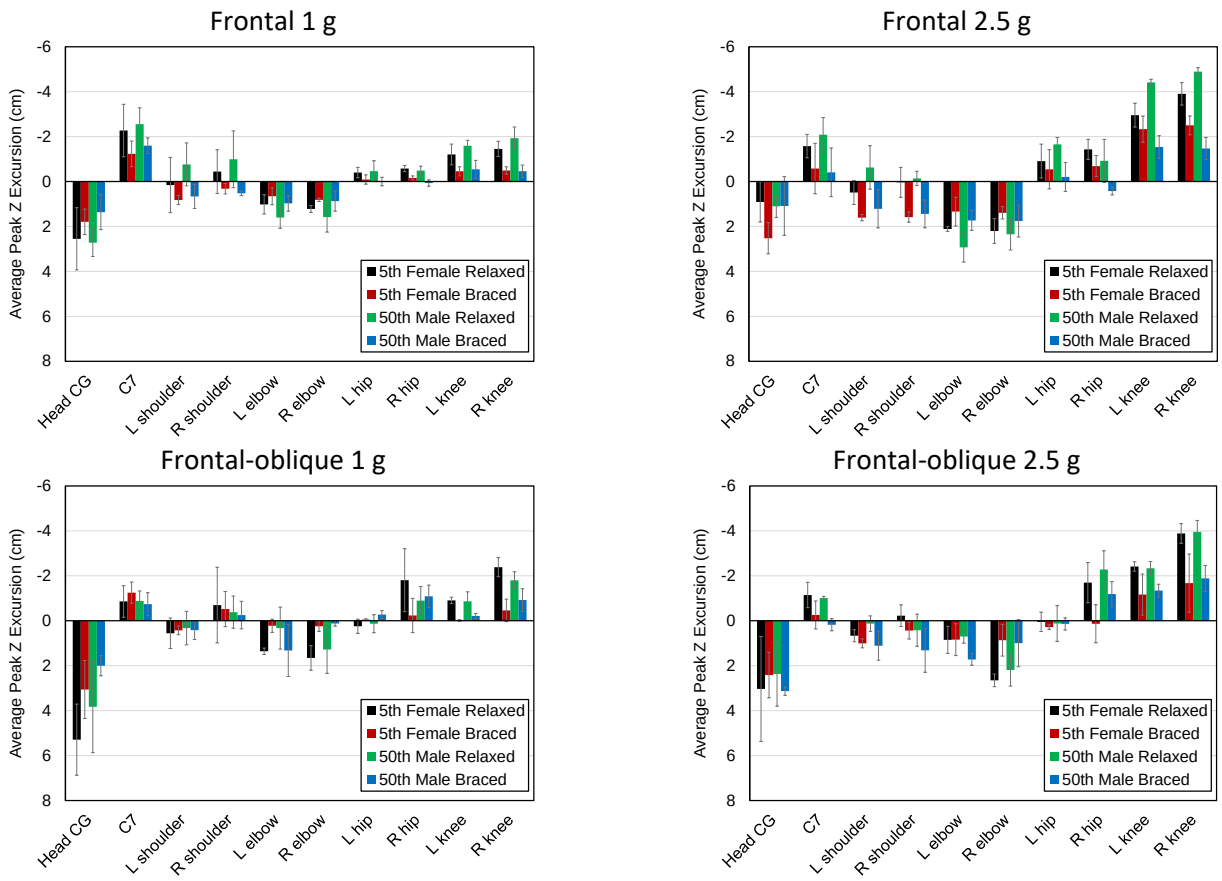


Fig. A10. Female and male average (± standard deviation) peak vertical excursions for the relaxed and braced tests. Excursions are limited to first day data only for all groups.