Can Vehicle Seat Loads Discriminate Between Occupants' Displacements in Non-Standard Postures During Low-Acceleration Manoeuvres?

Madeline Griffith, Thomas Seacrist, Valentina Graci

Abstract Autonomous driving will lead to a variety of non-standard occupant postures that will require novel countermeasures, such as adaptive restraints, which will require sensing of occupants' dynamic repositioning. This study aimed to understand if loads under the vehicle seat could discriminate occupants' position during low-acceleration manoeuvres. Seat loads were collected for: (1) 16 forward-leaning adults restrained with high-force, low-force, or no pre-pretensioning (PPT) in a 1 g frontal impact; and (2) five nominally, moderately, and severely reclined booster-seated children in a 2 g lateral-oblique impact. Net magnitude and direction of torque on the seat were calculated. In the frontal impact tests, a significant effect of PPT level was found, showing that torque magnitude was greater with low-force PPT (290 ± 42 Nm) than with no PPT (251 ± 37 Nm) ($p<0.0003$), and with high-force PPT (291 ± 46 Nm) than no PPT ($p<0.0002$), with no significance between low- and high-force PPT ($p>0.8$). In the lateral-oblique tests, no effect of seatback recline angle was found ($p>0.19$). Occupants' repositioning due to PPT in forward manoeuvres were detected by seat loads, but differences in occupants' displacement in reclined postures in lateral-oblique manoeuvres were not. Future studies are warranted to explore different postures, countermeasures and loading conditions.

Keywords Adaptive restraints, repositioning, seat torques, personalised restraints, out-of-position.

I. INTRODUCTION

Adult and paediatric vehicle occupants can assume a wide range of postures while travelling in a vehicle [1-3]. The rise of autonomous vehicles may lead to an even greater prevalence of non-standard seating postures as occupants may opt to assume more comfortable positions, such as reclined seating, or may engage in secondary tasks that lead to a forward-leaning posture [4-5]. Non-standard seating postures have been found to influence crash injury risk [5-6] as they are the equivalent of current out-of-position postures. In a study evaluating the influence of current vehicle occupant mass, stature, posture and bracing level on injury risk in frontal collision, occupant posture was found to be the most significant parameter affecting overall injury risk [6]. The high variability in injury outcome across postures was influenced by available excursion distance, restraint effectiveness, and contact with vehicle interior [6]. Therefore, novel countermeasures will need to provide protection to occupants in a wide range of sitting postures in future autonomous vehicles.

Recent efforts have been dedicated to developing and assessing the potential benefits of an adaptive restraint system [7-8]. The Advanced Adaptive Restraints System (AARS) developed for the National Highway Traffic Safety Administration (NHTSA) adapted the airbag cushion shapes, airbag deployment, and seat-belt load limiting to the occupant size, seating position, posture, crash type and crash severity [7]. Eleven out-of-position cases were assessed and though a reduced risk of injury was achieved in some cases, improvement was greater for the thirteen in-position load cases assessed [9]. Therefore, improvement of adaptive restraint performance is especially needed for out-of-position cases, which may require improved occupant posture-sensing capabilities. The AARS used a two-part sensing system to determine dummy position and posture: weight sensor units under the vehicle seat to calculate centre of gravity, and a three LED optical range finder [7]. Another, more recent effort to develop a personalised restraint control system is smart-RCS, developed by Veoneer, emotion3D, and AVL [8]. Similarly, this system optimises airbag deployment strategy based on criteria such as crash direction, crash intensity, occupant size, occupant position and occupant dynamics [8]. Occupant position and dynamics are collected by a 3D time-of-flight camera module [8].

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Although these systems show strong potential for optimising occupant safety, both rely on optical sensing in order to determine occupant position and posture, which may not be able to reliably determine an occupant's non-standard position or posture if the sensors are obscured by objects in the vehicle interior. In the NHTSA AARS assessment, the anthropomorphic test device (ATD) position and posture could only be determined when the steering wheel was oriented so that it did not obscure the optical sensors' field of view, and the sensor parameters were dependent on the tilt and telescoping adjustment of the steering column [7]. In non-controlled, naturalistic driving scenarios there may be additional objects in the vehicle interior (e.g. a book or tablet in the occupant's hands or a bag on the occupant's lap) that may impact optical sensor measurements or obscure camera views and be difficult to predict or account for. Additionally, the assessments in [7] were conducted using ATDs in a static pre-test position, which did not account for voluntary (e.g. postural changes) or reflexive (e.g. bracing) motions that may occur in human occupants. These motions may pose additional challenges by increasing the potential for occupants to shift out of camera view; moreover, centre of gravity measurements cannot be updated during occupant motion due to non-zero shear forces.

Previous studies have evaluated the motion of human volunteers in non-standard seating postures in low-acceleration manoeuvres. Graci *et al*. [10] found that during a frontal pre-crash pulse, forward-leaning adult occupants had a greater probability of moving their head and trunk more rearward in the presence of a pre-pretensioner (PPT) equipped seat belt than without a PPT, and with a higher force level of PPT than with a lower force level of PPT. This study also showed that at discrete time points during the sled pulse, the head and trunk had the furthest rearward displacement with the high-force PPT, and the least rearward displacement with no PPT; on average, the trunk position 250 ms after the sled pulse began was 82 mm rearward of the forward-leaning initial position with the high-force PPT, versus 22 mm rearward of the forward-leaning initial position with the low-force PPT and 64 mm forward of the forward-leaning initial position with no PPT [10]. Additionally, the same group [11] found that during a far-side lateral-oblique pre-crash pulse, booster-seated paediatric occupants had decreased maximum lateral head and trunk displacement out of the belt with increasing seatback recline angle; on average, the maximum lateral displacement of the trunk decreased from 160 mm in the nominal (25°) seatback angle to 132 mm in moderately reclined (45°) seatback angle and to 108 mm in the severely reclined (60°) seatback angle. In both studies, the reported displacements occurred during the pre-crash pulse and may have been influenced by occupants' muscle activation.

As adaptive and personalised restraints continue to be developed and optimised for future vehicles, it is important to consider not only out-of-position initial posture, but also dynamic repositioning that may occur in and from these non-standard postures. Existing methods to sense occupant position and posture, such as optical sensing and centre of gravity calculations, may be unreliable in dynamic environments due to obscured cameras and non-zero shear forces, respectively. Thus, investigating additional methods to sense and detect occupants' posture and dynamic repositioning that can supplement existing methods may be beneficial.

One potential method for augmenting the detection of occupant position is to incorporate load cells under the vehicle seat. Load cells under the vehicle seat are advantageous because they can (1) account for non-zero shear forces and (2) multiple load cells can be used to calculate a net torque: one magnitude and one direction to describe and interpret the loads on the seat. Therefore, the aim of this study was to understand if/how the torques applied to the vehicle seat by vehicle occupants can discriminate occupants' repositioning from non-standard postures during different sled-simulated, low-acceleration manoeuvres. A secondary analysis was performed on existing data from two studies to understand how the torques on the vehicle seat differ across testing conditions and how those compare to previously published kinematic differences [10-11].

II. METHODS

This study was approved by the Institutional Review Board at the Children's Hospital of Philadelphia. For this study, a secondary analysis was performed on data previously collected by our group for two separate studies, as described in the subsections below; primary analyses of the kinematics, muscular response, and seatbelt loads have been previously published [10-11]. For both studies included in this secondary analysis, data were collected with human volunteers on a pneumatically actuated, hydraulically controlled low-speed crash sled [12]. A front passenger vehicle seat (2012 Volvo S60) equipped with four 3-axis load cells (3A120-1KN-C11, Interface Force Measurement Solutions, Scottsdale AZ, USA) collected loads under the four corners of the seat. The load data were sampled at 10 kHz using an onboard TDAS Pro data acquisition system (DTS Inc, Seal Beach, CA). Two different testing configurations from two previous studies [10-11] were used: frontal impact tests with PPT, and lateral-oblique impact tests with reclined seatback.

Frontal Impact Tests with PPT

Sixteen forward-leaning adult occupants (8 male: age 20–28 years, weight 79.5 ± 2.6 kg; 8 female: age 19–35 years, weight 65.0 ± 4.4 kg) participated in this portion of the study. Participants were included if their height and weight were within ±10% of the 50th percentile of the US population for their age and sex [13] and they had no neuromuscular or musculoskeletal conditions. Participants were exposed to a 0.95 g frontal pre-crash pulse, representing maximum emergency braking deceleration, and were restrained with a three-point seat belt equipped with a reversible electric pre-pretensioner (PPT) in the retractor (R230 PPMI, Autoliv Inc., Stockholm, Sweden).

Three testing conditions were examined: no PPT; low-force level PPT (approximately 100 N); and high-force level PPT (approximately 300 N) (Table I). Prior to each test, participants were instructed to lean forward so that their trunk was angled approximately 40 degrees forward of the vehicle seatback, which was oriented in a nominal configuration (approximately 22 degrees from the vertical) (Fig. 1). This forward trunk angle was standardised across tests and participants using a rigid 40-degree wood frame aligned with the vehicle seatback. Participants were instructed to maintain their forward-leaning posture until the event occurred. A full description of methods is reported in [10]. Each of the three test conditions were also conducted with no occupant in the sled to record the forces due to the sled acceleration and PPT activation. The resulting forces were subtracted from the forces collected with occupants to zero out the forces applied to the seat by the different levels of PPT activation.

TABLE I
Test Matrix for adult occupants

Seatbelt condition	Impact	Repetitions
No PPT	1 g frontal	2
Low-force level PPT (100 N)	1 g frontal	2
High-force level PPT (300 N)	1 g frontal	2


(A)

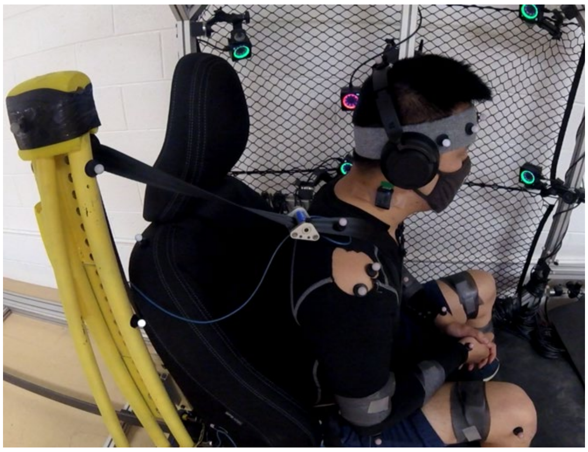

(B)

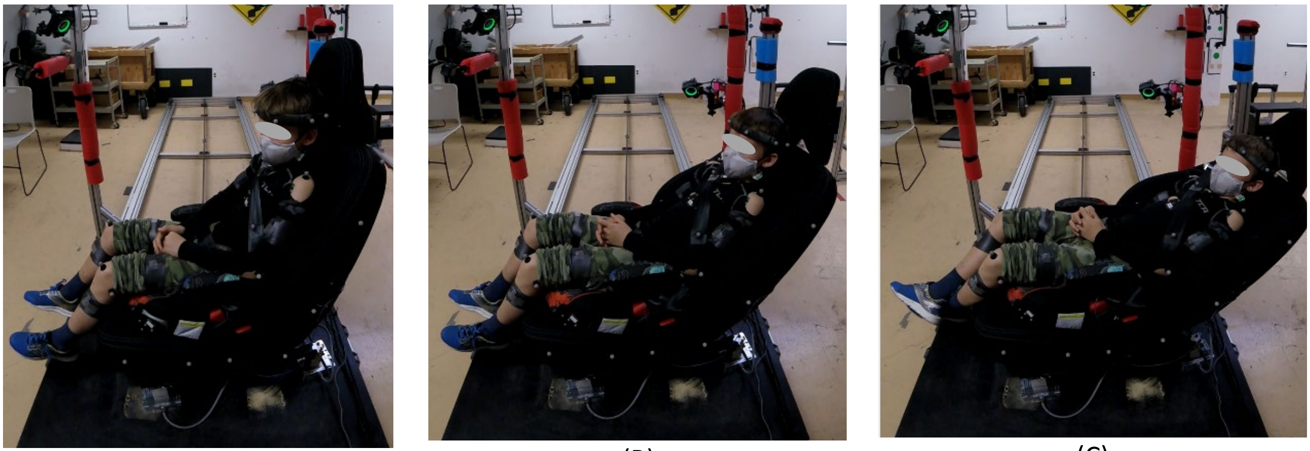
Fig. 1. (A) Low-speed crash sled in frontal impact testing configuration, including front passenger vehicle seat, load cells under the corners of the vehicle seat, and a B-Pillar structure with PPT-equipped three-point seatbelt, and (B) occupant seated in forward-leaning position.

Lateral-Oblique Impact Tests with Reclined Seatback

Five reclined booster-seated children (age 6–8 years, weight 25.0 ± 3.5 kg) participated in this portion of the study. Participants were included if their height, weight and BMI were between the 5th and 95th percentile for their age and sex and they had no neuromuscular or musculoskeletal conditions. Participants were exposed to a 2 g far-side lateral-oblique (80 degrees from frontal) pre-crash pulse, representing a low-speed far-side impact. The participants were seated on a low-back belt-positioning booster seat (BPB) placed on the vehicle seat and restrained with a three-point seat belt. A custom adjustable fixture was used to simulate an integrated seat belt. Three seatback recline angles were tested: nominal (25 degrees); moderately reclined (45 degrees); and severely reclined (60 degrees) (Table II; Fig. 2). A full description of methods is reported in [11]. Each of the three test conditions were also conducted with no occupant in the sled to record the forces due to the sled acceleration, BPB, and reclined seatback. The resulting forces were subtracted from the forces collected with occupants to zero out the forces applied to the seat by the different seatback recline angles.

TABLE II
Test Matrix for BPB-seated paediatric occupants

Seatback Recline Angle	Impact	Repetitions
Nominal (25°)	2 g lateral-oblique (80° from frontal)	2
Moderate (45°)	2 g lateral-oblique (80° from frontal)	2
Severe (60°)	2 g lateral-oblique (80° from frontal)	2



(A) (B) (C)

Fig. 2. Low-speed crash sled in lateral oblique testing configuration with front passenger vehicle seat, load cells under the corners of the vehicle seat, and simulated integrated seat-belt structure, with paediatric occupant seated in a BPB with (A) nominal, (B) moderate, and (C) severe seatback recline angles.

Data Analysis

Load data were filtered using a 4-pole Butterworth filter (SAE J211) with a frequency class of 60. Loads with no occupant were subtracted out from corresponding testing conditions in order to remove forces applied by the sled acceleration and by the PPT activation or reclined seatback and therefore keep only the forces applied by the occupant. Net magnitude and direction of torque on the seat were calculated relative to the centre of the vehicle seat pan. For the frontal impact tests with PPT, a Repeated Measures two-way ANOVA was performed on the peak torque magnitude to understand the effects of occupant Sex and PPT level and to compare those to previously published kinematic results [10]. In addition, to account for the variation in mass between female and male occupants, load data were scaled to the 50th percentile U.S. male [13] using the technique developed in [14], and an additional Repeated Measures two-way ANOVA was performed on the scaled torque magnitude to understand the effects of occupant Sex and PPT level. For the lateral-oblique impact tests with reclined seatback, another Repeated Measures one-way ANOVA was performed on the peak torque magnitude to understand the effect of Seatback Recline Angle and to compare that to previously published kinematic results [11]. Statistical results on maximum torque are compared only within testing configurations. Direction of torque was described and compared qualitatively.

III. RESULTS

Frontal Impact Tests with PPT

Exemplar occupant displacements for each of the PPT conditions are depicted in Fig. 3, showing greater rearward displacement with the PPT (Fig. 3(B), 3(C)) than without it (Fig. 3(A)), and a greater rearward displacement with the high-force PPT (Fig. 3(C)) than with the low-force PPT (Fig. 3(B)). Full kinematic results are reported in [10].

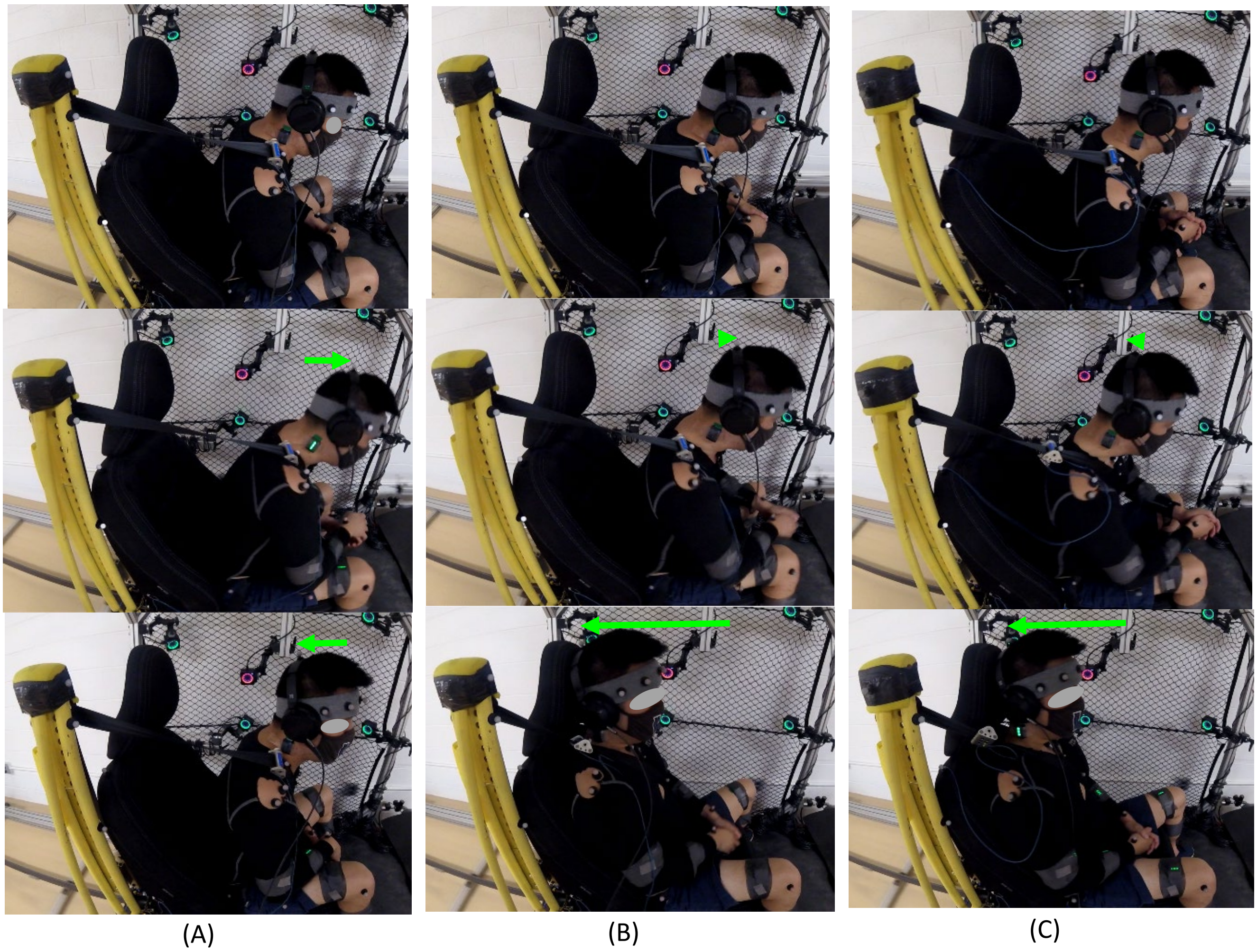


Fig. 3. Photos depicting exemplar occupant displacements, from initial position through maximum forward excursion during the sled pulse through final position (top to bottom) with (A) no PPT, (B) low-force PPT, and (C) high-force PPT. Arrows are used to indicate magnitude and direction of movement from previous picture.

For the frontal impact tests with PPT, magnitude (in Nm) and direction (in the plane of the vehicle seat pan) of torque on the seat, separated by PPT condition and separated by Sex, are shown in the polar plots of Fig. 4 and Fig. 5, respectively. For all PPT and Sex conditions, peak torques occurred approximately in the forward direction.

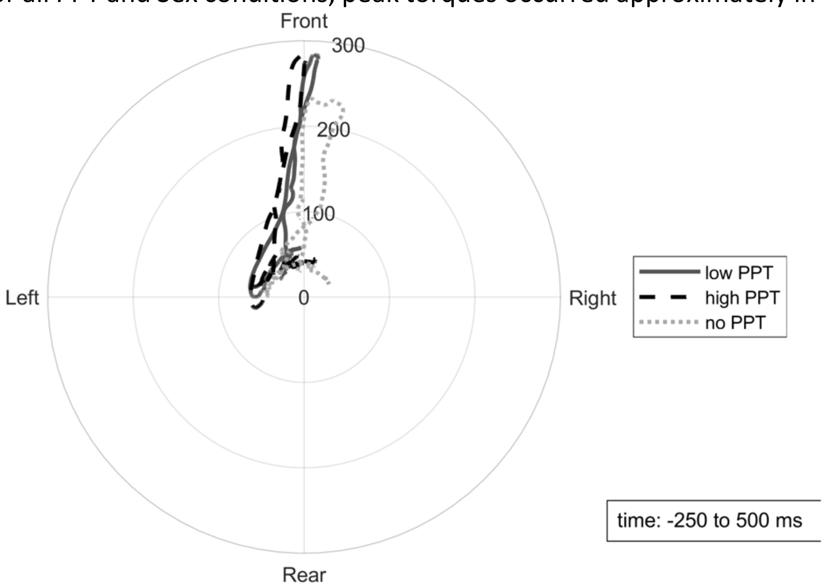


Fig. 4. Polar plot indicating direction in the plane of the seat pan and magnitude (Nm) of the torque applied to the seat over the duration of the frontal impact tests, separated by PPT condition, for the 16 adult subjects.

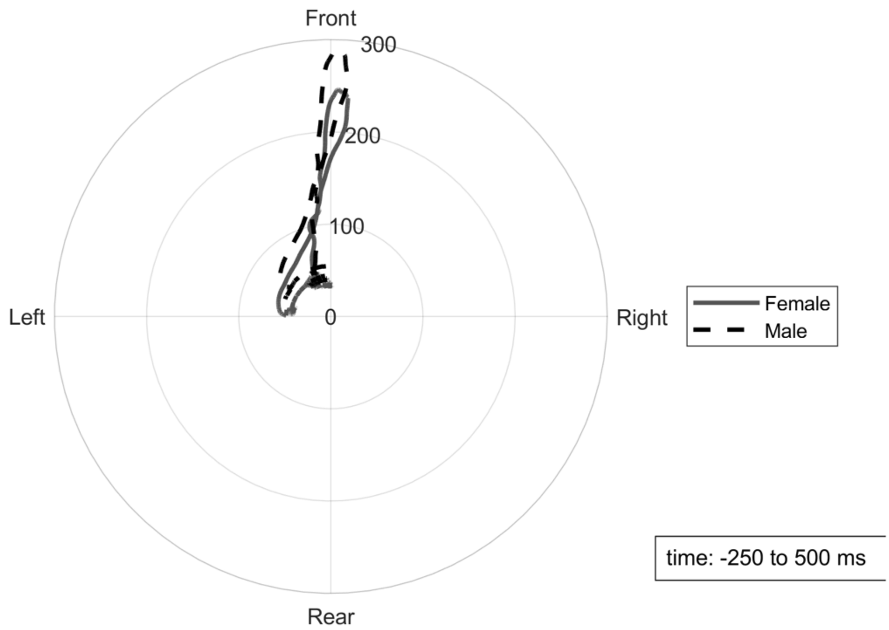


Fig. 5. Polar plot indicating direction in the plane of the seat pan and magnitude (Nm) of the torque applied to the seat over the duration of the frontal impact tests, separated by occupant Sex, for the 16 adult subjects.

In the frontal impact tests with PPT, a statistically significant main effect of PPT level was found on the peak magnitude of the torque on the seat (Fig. 6), showing that the peak seat torque magnitude was greater with low-force PPT (290 ± 42 Nm) than with no PPT (251 ± 37 Nm) ($p<0.0003$), and also greater with high-force PPT (291 ± 46 Nm) than with no PPT ($p<0.0002$), with no significance between peak torque magnitudes with the low-force PPT and the high-force PPT ($p>0.8$).

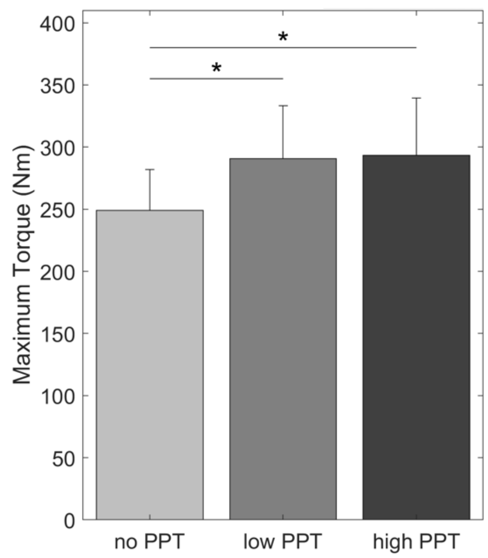
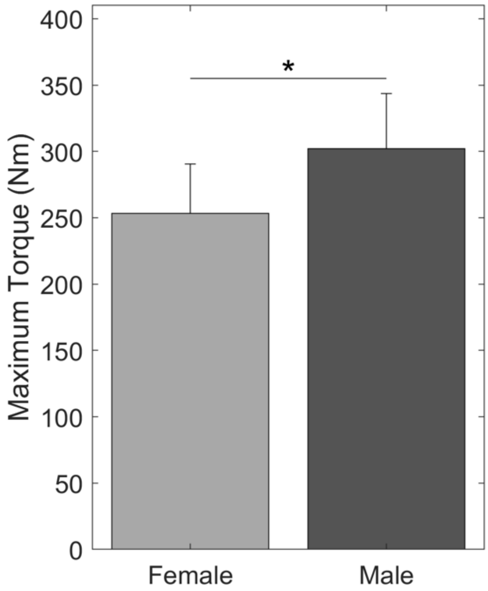
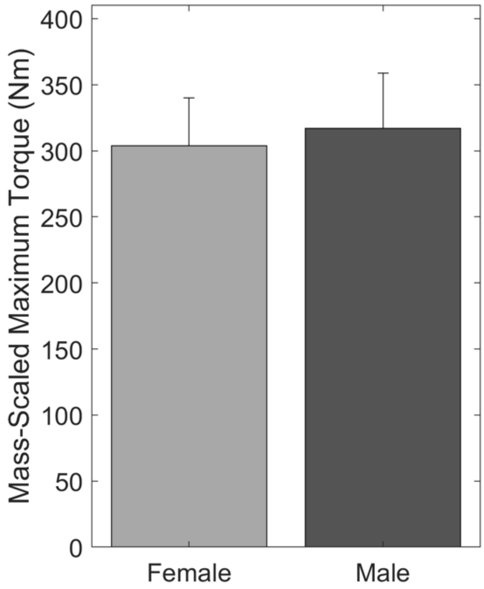


Fig. 6. Maximum magnitude of torque applied to the seat, separated by PPT condition, in the 16 adult subjects during the frontal impact tests.

A statistically significant main effect of occupant Sex was also found on the peak magnitude of the torque on the seat (Fig. 7(A)), with higher peak seat torque magnitude in male subjects (300 ± 42 Nm) than female subjects (251 ± 38 Nm; $p<0.0003$). There was no statistically significant effect of occupant Sex found on the mass-scaled peak torque magnitude ($p>0.3$; Fig. 7(B)).



(A)

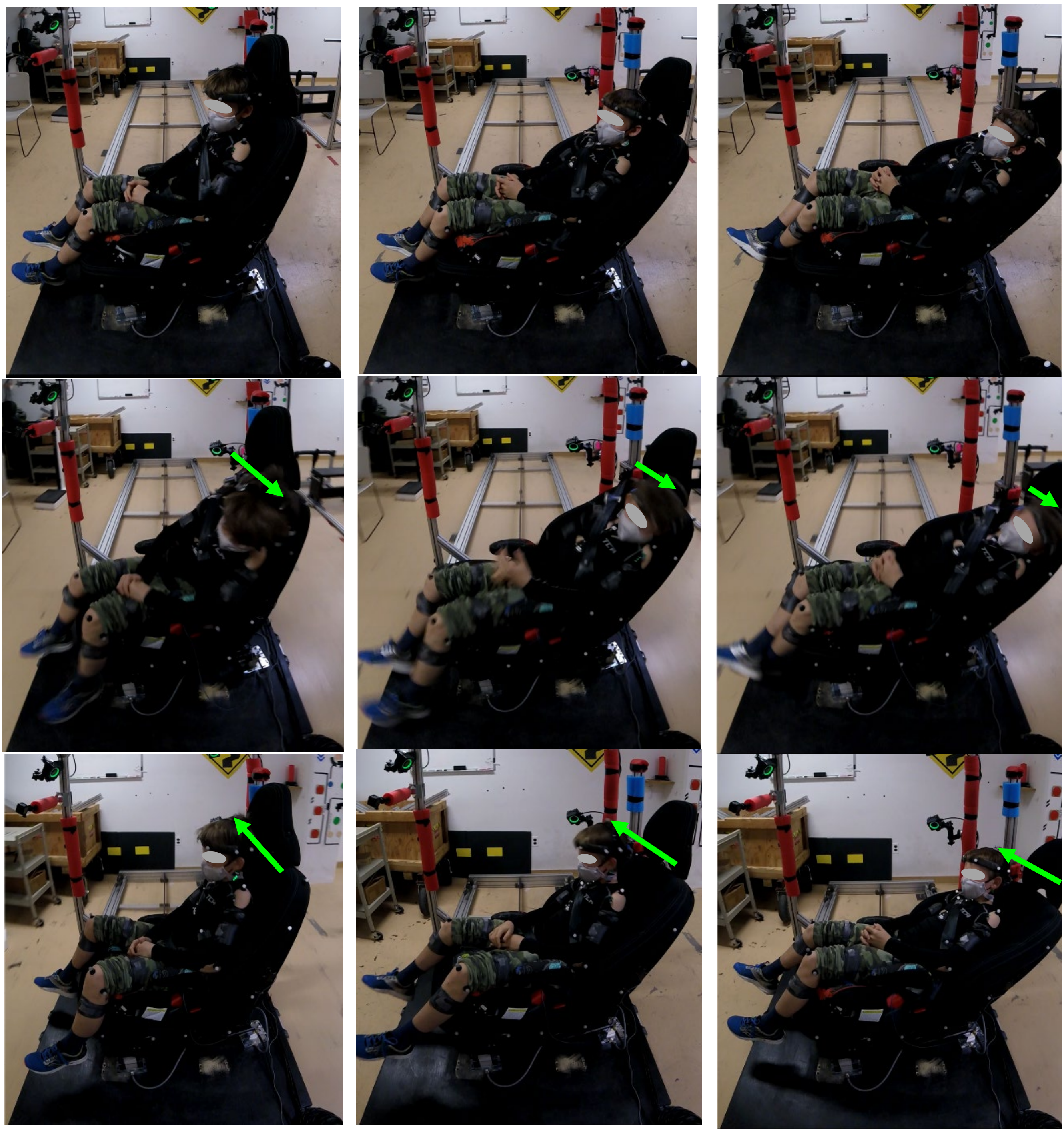


(B)

Fig. 7. Maximum magnitude of torque applied to the seat, separated by occupant Sex, in the 16 adult subjects during the frontal impact tests, (A) without mass-scaling the load data and (B) with mass-scaling the load data.

Lateral-Oblique Impact Tests with Reclined Seatback

Exemplar occupant displacements for each of the seatback recline angles are depicted in Fig. 8, showing reduced lateral displacement with increasing seatback recline angle. Full kinematic results are reported in [11].



(A) (B) (C)

Fig. 8. Photos depicting exemplar occupant displacement, from initial position through maximum lateral displacement through final position (top to bottom) with (A) nominal seatback recline angle, (B) moderate seatback recline angle, and (C) severe seatback recline angle. Arrows are used to indicate magnitude and direction of movement from previous picture.

For the lateral-oblique tests with a reclined seatback, the magnitude (in Nm) and direction (in the plane of the vehicle seat pan) of torque on the seat, separated by seatback recline angle, are shown in the polar plot of Fig. 9. For all seatback recline angles, peak torques occurred approximately in the left (inboard) direction. There was no statistically significant effect of seatback recline angle found on the peak magnitude of the torque on the seat ($p>0.19$).

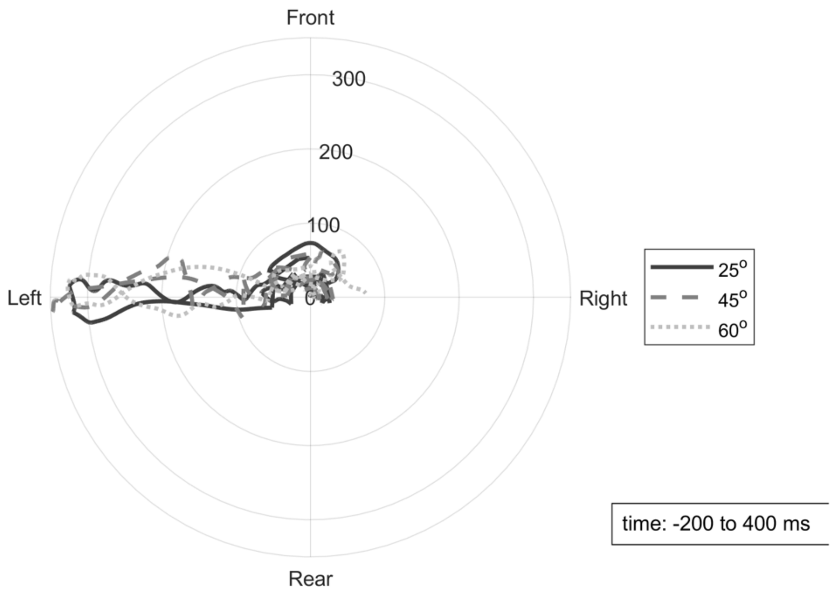


Fig. 9. Polar plot indicating direction in the plane of the seat pan and magnitude (Nm) of the torque applied to the seat over the duration of the lateral-oblique impact test, separated by seatback recline angle, for the five child subjects.

IV. DISCUSSION

The aim of this study was to understand if/how the torques applied to the vehicle seat by vehicle occupants can discriminate occupants' displacements from non-standard postures during different sled-simulated, low-acceleration manoeuvres. A secondary analysis was performed on existing data from two studies in order to understand how the torques on the vehicle seat differ across testing conditions and how those compare to previously published kinematic differences [10-11].

In forward-leaning occupants, the presence of the PPT, but not its force level, could be discriminated by the torques applied to the vehicle seat by the occupant. The torque magnitude was greater in the presence of PPT, suggesting that the occupant's pelvis pushed forward while their trunk moved rearward due to the PPT. Previous analysis of the kinematics of these forward-leaning occupants found that at discrete time points during the sled pulse rearward trunk displacement was greater with either force-level of the PPT than without it (at 250 ms, mean difference of -146 mm with the high-force PPT and -86 mm with the low-force PPT), and greater with the high-force PPT than with the low-force PPT (at 250 ms, mean difference of -60 mm) [10]. While mean differences in the seat torques of 39-40 Nm between each of the PPT conditions and the no-PPT condition suggest a capability to detect this difference in rearward displacement with and without the PPT, no difference in seat torques was found between the two levels of PPT, suggesting that the difference in rearward displacement between the two PPT levels could not be detected, potentially due to the smaller difference in displacement. Similarly, previous analysis of the kinematics of the reclined child occupants in a lateral-oblique manoeuvre found that lateral trunk displacement decreased with increasing seatback recline angle by a mean of 28 mm from nominal to moderate recline, and by a mean of 52 mm from nominal to severe recline [11]; however, no corresponding difference was found in the seat torques applied by the occupant, suggesting that this difference in lateral displacement cannot be detected. It is possible that the differences in occupant displacement with different seatback recline angles were not able to be discriminated by the torques on the vehicle seat because the lateral displacement of the occupant's head and trunk on the seatback was relatively small and did not produce sufficient change on the loads applied to the seat pan.

Although specific differences in kinematics were not always detected by the seat torques within the same testing configuration, larger scale differences were evident. While the difference in torque between PPT force levels was not detected, a difference in torque based on the presence of the PPT as a triggered countermeasure could be determined. The difference in rearward displacement was greater between conditions with either force level of PPT and no PPT than between the two force levels of PPT, suggesting that larger differences in occupant repositioning may be able to be detected by seat loads, but smaller differences may not. Within the forward-leaning adult occupants, a difference in seat torque magnitude was detected between female and male occupants showing that females applied less torque to the seat. However, this difference was not present when the load data were scaled by mass, suggesting that the difference detected by the seat torques was the difference between occupants' size/weight rather than inherent difference between sexes, as there was a mean weight difference of 14.5 kg between male and female subjects prior to mass scaling. Additionally, the different impact directions of the two loading conditions, frontal and lateral-oblique, showed differences in torque direction that reflected those impact directions and the direction of the occupants' overall kinematics [10-11].

The findings of this study suggest that, although seat torques may not be sensitive enough to be used as the only sensing method of occupant position and posture, they could complement other methods of sensing changes in non-standard occupant postures. Seat torques could serve as a backup or redundant measurement to posture-sensing systems, as benefits include a simple calculation, no susceptibility to camera/sensor obscuring, and the ability to be calculated during dynamic repositioning. In addition to providing some information on occupant displacement from non-standard postures, seat torques may also complement sensors to inform other characteristics, such as occupant size and crash direction. Personalised restraint systems such as smart-RCS and NHTSA's AARS utilize multiple sources of information such as seat track sensing, weight sensing, and seatbelt webbing payout to complement the system; seat torques may have additional benefit as a complementary source of information, but further studies and development are needed. This study represents the first effort to examine the sensing capability of seat torques by analysing differences in seat torques given differences in occupant displacement and shows the ability of seat torques to detect larger scale differences in occupant displacements, size, and movement direction between specific test conditions. However, more work is needed to translate seat torque results to data containing the quantitative position of the occupant within the vehicle, which can directly inform robust restraint optimisation. Future studies are warranted to explore vehicle seat loads with a variety of other non-standard occupant postures and with different countermeasures, occupant populations and loading conditions to understand the degree to which vehicle seat loads are useful to predict occupants' position.

This study had some limitations. Although testing conditions with a wide range of characteristics were examined, the impact of changing each of these characteristics could not be directly compared as the two primary testing configurations used not only different non-standard postures but also different countermeasures, occupant populations, impact directions, and impact severities. The current study is a novel exploratory analysis using existing data; therefore, the test matrices were not optimised for evaluating the effectiveness of seat torques as a sensing mechanism for all occupant positions and postures. Additionally, seat loads were zeroed to the occupants' initial testing posture and position as they were collected. Therefore, initial static forces from these non-standard postures could not be identified or analysed; rather, only the forces generated during dynamic motion could be detected.

V. CONCLUSIONS

This study employed a novel method of analysing vehicle seat loads to understand vehicle occupants' non-standard postures. By analysing the difference in the torque applied to the seat, this study offers insight into how occupants position their weight, which may complement other sensing methods for advanced safety measures, such as personalised restraints.

VI. ACKNOWLEDGEMENTS

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