Repositioning Forward Leaning Occupants with a Pre-Pretensioner Belt in Static Conditions

Witmer M[1,2,3], Griffith M[1], Graci V.[1,3]
[1]Center for Injury Research and Prevention, Children's Hospital of Philadelphia
[2]College of Engineering, Electrical and Computer Engineering, Drexel University
[3]School of Biomedical Engineering, Science and Health System, Drexel University

ABSTRACT

Extreme out-of-position pre-crash postures may need high force pre-pretensioner (PPT) for effective repositioning (Mishra et al., 2023). To avoid applying a high force on the chest, we hypothesized that in case of these extreme postures the PPT may be activated in absence of a pre-crash motion as cautionary measure. Therefore, the aims of this study were: 1) to understand the effect of the PPT in repositioning a forward leaning occupant in static conditions, and 2) to characterize occupants' kinematic variability during repositioning. Sixteen healthy volunteers (8 males, 8 females, 23.8 ±4.2 years old) were seated with a 40° forward posture on a vehicle seat and restrained with a 3-point seat belt equipped with a PPT. Two PPT seatbelt conditions were examined: low PPT (100 N), and high PPT (300 N). Head and trunk rearward displacements relative to the initial forward leaning position at 350 ms from PPT onset were collected with a 3D-motion capture system and compared between sexes, repetitions, and PPT levels with Repeated Measure 3-way ANOVAs (p-level= 0.05). Head and trunk rearward displacements were greater with the high PPT (head -93.8 ± 9.3 mm, trunk -78.7 ± 6.7 mm) than the low PPT (head -44.6 ± 8.9 mm, trunk -39.7 ± 7.6 mm) ($p<0.001$). There were no statistically significant differences between sexes ($p>0.19$), repetition ($p>0.28$), and no interaction effects ($p>0.18$). There was greater inter-subject variability in the low (head -109.5 to -22.1 mm, trunk -105.0 to -17.5 mm) compared to high PPT (head -175.0 to -62.5 mm, trunk -128.4 to -54.8 mm). Although no sex differences were found, the high inter-subject variability suggests that PPT timing and force level might not be designed as one-size-fits-all. This study shows that triggering the PPT when the vehicle is travelling at a constant speed could reduce the PPT force needed to reposition forward leaning occupants during pre-crash maneuvers.

INTRODUCTION

With the increasing availability of advanced driving-assistant systems (ADAS), it is not unimaginable to see many vehicles becoming fully autonomous. A recent study was conducted to examine drivers' comfort in highly autonomous vehicles (HAV) to meet their needs in driving and non-driving related tasks (Sun et al., 2021). The experimenters asked participants which activities they expected to be able to accomplish when in an HAV. The main responses ranged from relaxing to social and work activities. The findings of this study showed that in HAV occupants tend to be

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less attentive to the vehicle motion and more relaxed, which has the potential to lead the occupants to assume a wide variety of seating postures. Nie et al. (2020) conducted a study about occupant seating preferences (i.e., posture, orientation, seatbelt). When the participants were asked about their favorable seating positions, reclining or leaning forward while engaged in a secondary task where common answers (Nie et al., 2020). Occupants' preferences of posture and activities in HAV may potentially result in injuries when impacts occur if current restraints are not modified to accommodate such postures.

There is a growing body of literature that investigates forward leaning occupants and potential seatbelt related countermeasures. A recent study conducted by Graci et al. (2022a) explored how auditory warnings and pre-pretensioner (PPT) seat belt in a pre-crash scenario could reposition occupants rearward from a forward leaning position. Both male and female volunteers experienced a pre-impact sled-pulse with different PPT force levels (100 N and 300 N). They found that occupants were repositioned about 80 mm rearward in 250 ms with a 300 N PPT. The main result of this study is that the PPT was effective at repositioning subjects during a pre-crash maneuver even though the subjects were not in the nominal position with their back touching on the seatback (Graci et al., 2022a). However, 80 mm within 250 ms time window may not be enough to reposition occupants in different types and severities of pre-crash maneuvers. A more recent study from some of the same authors used the 50th percentile male Human Body Model (HBM) to understand if a high-force PPT (i.e., 600 N) could reposition an occupant to an upright posture from a 29˚ forward leaning position during an automated emergency braking (AEB) maneuver. The authors found that occupants were repositioned rearward by the high-force PPT up to 220 mm in 200 ms (Mishra et al., 2023). A high-force PPT seems to be able to reposition occupants more rearward than the lower force level of PPT, 100-300 N, used in Graci et al. (2022a). However, a full comparison between the two above mentioned studies cannot be made as they have several methodological differences. For instance, in Graci et al. (2022a), the breaking pulse had a very short ramp time (90 ms), which corresponds to a low-acceleration impact rather than a AEB (Graci et al., 2021). In Mishra et al. (2023) the HBM was positioned 29˚ forward compared to the occupants in Graci et al. (2022) who were placed in a more extreme forward leaning posture of 40˚. Nevertheless, AEB acceleration is not the same across make and model vehicle years (Graci et al., 2021, Kidd et al., 2023), so future studies are needed to understand the repositioning effectiveness of different PPT force levels across different types of AEB. It is plausible that PPT forces above 300 N may need to be employed in AEB pulses with a high-jerk level and a short ramp time to reposition occupants from extreme forward leaning position. However, it is unclear if/how high-force PPTs can be tolerated by the variety of occupant populations from children to older adults.

Therefore, in this study we hypothesized that we could use low force PPT in the event of extreme out-of-position postures assumed by the occupants in static conditions, simulating a vehicle is traveling at constant speed.

A study by Hellenbrand et al. (2023) examined the effectiveness of a pyrotechnic pretensioner on occupants leaning 26 cm forward in static conditions (i.e., no sled motion or vehicle maneuver present) on a vehicle production seat. Participants' trunks moved rearward between 4.6 and 8.1 cm within 160-180 ms from the pretensioner onset. The authors found that subjects' rearward motion was correlated to body size between 50 and 160 ms from the pretensioner onset. After that, the rearward motion was highly variable between subjects, indicating that the rearward motion after 160 ms was more influenced by occupants' behavior than body size. However, pyrotechnic pretensioners only fire in crash situations not while the occupants are traveling at constant speed (i.e., static conditions). Therefore, it is unclear how to extend these results to real-world scenarios (outside laboratory settings).

Another study done by Good et al. (2008), examined the effect of PPT force levels on torso kinematics of forward leaning human volunteers with three different anthropometries (5th percentile female, 50th percentile male, and 95th percentile male) in static conditions. Subjects were asked to lay on their side (the authors claimed they wanted to avoid the influence of gravity on the rear motion) on an apparatus with a 200 N PPT. The 5th percentile female group was displaced a maximum of 54.3˚ in 0.78 s, 50th percentile male group was displaced a maximum of 57.6˚ in 0.95 s, and 95th percentile male group was displaced a maximum 42.2˚ in 0.91 s. The authors concluded that occupant size influenced repositioning time of the torso. However, the differences in body size among their participants may have masked behavioral differences in the rearward motion.

Most of the studies conducted in static conditions did not extensively examine muscle activation. Without muscle activation, it is not possible to tease out the kinematics resulting from the volitional motion of the occupants and those occurring by inertia. It is not clear how muscle activity contributes to the occupant motion observed when the PPT is activated.

Therefore, the aims of this study were to examine the effect of different PPT force levels on the kinematics and muscle activity of forward leaning occupants on a production vehicle seat in static conditions, and to characterize inter-occupants' kinematic variability when the PPT is activated.

METHODS

The Institutional Review Board of the Children's Hospital of Philadelphia reviewed and approved the study protocol. Sixteen healthy volunteers (8 males, 8 females, 23.8 ±4.2 years old, height 175.5 ± 6.8 cm, weight 72.3 ± 8.3 kg) participated in the study. The volunteers signed an informed consent form and were verbally screened for exclusion criteria.

The participants sat on a production vehicle seat and were restrained with a 3-point seatbelt within a lab-simulated occupant compartment (Graci et al., 2022a). The 3-point seatbelt was equipped with a reversible electronic pre-pretensioner (PPT) in the retractor (R230 PPMI, Autoliv Inc., Stockholm, Sweden). Two different PPT loads were used: 100 N (low-force PPT) and 300 N (high-force PPT).

An Optitrack Prime 13W 15-camera motion-capture system (200 Hz, NaturalPoint Inc., Corvallis, OR) was used to capture head and trunk kinematics. Photo-reflective markers were placed on a fabric headband that subjects wore. On the trunk markers were placed directly on the skin bilaterally on the acromion, and on suprasternal notch. Five markers were placed on the

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headband, 4 markers were placed on a small rigid ABS structure taped to the subjects' suprasternal notch.

Seat belt loads (shoulder, right and left lap belt) were recorded with lightweight belt load cells (Denton Inc, Rochester Hills, MI) sampled at 10 kHz and collected with the TDAS Pro data acquisition system (DTS Inc, Seal Beach, CA).

Electromyography (EMG) was used to record muscle activation from the following bilateral muscles: biceps, brachialis, deltoids, sternocleidomastoids, trapezii, femoris, and tibialis. Participants performed maximum voluntary isometric contractions (MVICs) for each muscle. Muscle activation during the task conditions were normalized to MVIC and expressed in percent of MVIC activation. The EMG data was detrended and filtered with a 2nd order recursive low pass Butterworth filter with a 6 Hz cut-off.

The participants were instructed to lean forward, and a 40° wood frame was used to standardize the trunk forward angle. One side of the frame was placed in line with two markers on the seatback: one marker at the bottom of the seatback near the seat bight and one marker on the headrest. The other side of the frame was aligned with the right shoulder marker of the forward leaning occupants. Participants were instructed to remain in a forward position.

An acoustic warning was deployed in every trial at the same time as the PPT. The warning was an Acoustic Startling Pre-Stimulus (ASPS), which consisted of a 105 dB tone played for 40 ms and was delivered through noise canceling headphones (Surface Headphones 2, Microsoft Corporation). Participants were told to relax and were engaged in light conversation during a relaxation period of approximately 4-10 minutes between trials.

All participants underwent 6 static trials: 2 with no PPT (ASPS only), 2 with low PPT, and 2 with high PPT (Table 1). ASPS only conditions served as catch trials to avoid subjects' anticipation and familiarization with the PPT activation.

Table 1: Test Matrix

	Catch Trials	**Low PPT**	**High PPT**
Females	2	2	2
Males	2	2	2

The dependent measures considered in the study were the following: head and trunk position in the sagittal plane at 350 ms from PPT triggering time, mean EMG muscle activation and mean seatbelt shoulder load, both calculated within the first 300 ms from the PPT triggering time. Head and trunk positions was referenced to the initial forward leaning position before PPT activation (i.e., averaged head and trunk initial position calculated over the interval of 250 ms before PPT onset).

Mixed-Model Repeated Measure 3-way ANOVAs were used to understand the effect of three independent factors: Sex (between-subject), PPT force-levels and Repetition (within-subject) on all dependent measures. Pairwise comparisons were performed with Tukey's Honestly Significant Difference (HSD) tests. P-level was set at 0.05.

RESULTS

Participants moved rearward in the sagittal plane in both PPT conditions (Figure 1). The head moved rearward approximately 45 mm and 94 mm from the initial forward leaning position in the low and high PPT conditions, respectively. The trunk moved rearward approximately 40 mm and 79 mm from the initial leaning forward in the low and high PPT conditions, respectively (Table 2).

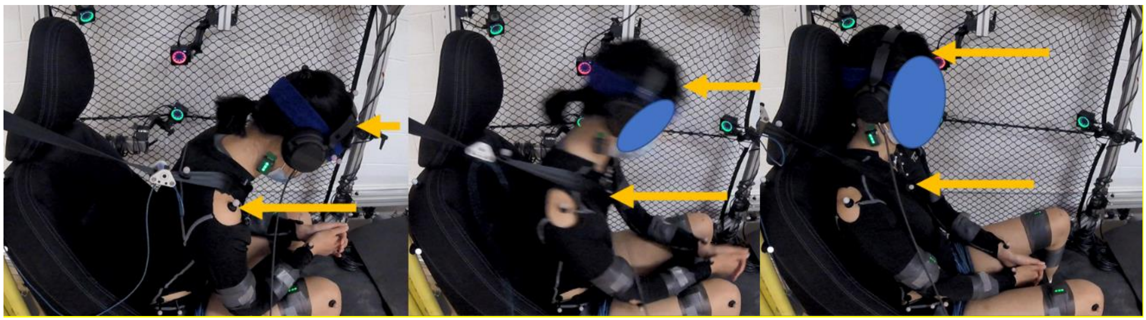

Figure 1: Exemplar subject being repositioned by the PPT: from left to right, initial position, motion rearward, final position.

The rearward head and trunk displacements were greater with the high PPT than the low PPT ($p<0.0001$, Table 2).

Table 2: Means (SD) of head and trunk rearward position from initial position in each PPT condition. Negative numbers indicate rearward motion.

	Low PPT	High PPT	p-value
Head position (mm)	-44.6 ± 8.9	-93.8 ± 9.3	<.0001
Trunk position (mm)	-39.7 ± 7.6	-78.7 ± 6.7	<.0001

The effect of Sex, Repetition, and any interaction between factors were not statistically significant ($p> 0.2$, Table 3).

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Table 3: Means (SD) of head and trunk rearward position from initial position for each sex. The differences between PPT conditions across sexes were not statistically significant ($p>0.02$). Negative numbers indicate rearward motion.

	Females		**Males**	
	Low PPT	**High PPT**	**Low PPT**	**High PPT**
Head position (mm)	-53.9 ± 13.9	-94.3 ± 12.8	-35.4 ± 9.0	-93.2 ± 13.0
Trunk position (mm)	-46.5 ± 12.3	-77.0 ± 9.9	-32.9 ± 5.8	-80.4 ± 7.6

Inter-subject variability found in the head position ranged between 22.1-109.5 mm in the low PPT condition (Figure 2, top left) and it ranged between 62.5-175 mm in the high PPT condition (Figure 2, top right). The trunk position also showed inter-subject variability: in the low PPT condition, the trunk position ranged between 17.5-105 mm (Figure 2, bottom left) and in the high PPT condition, the trunk position ranged between 54.8-128.4 mm (Figure 2, bottom right).

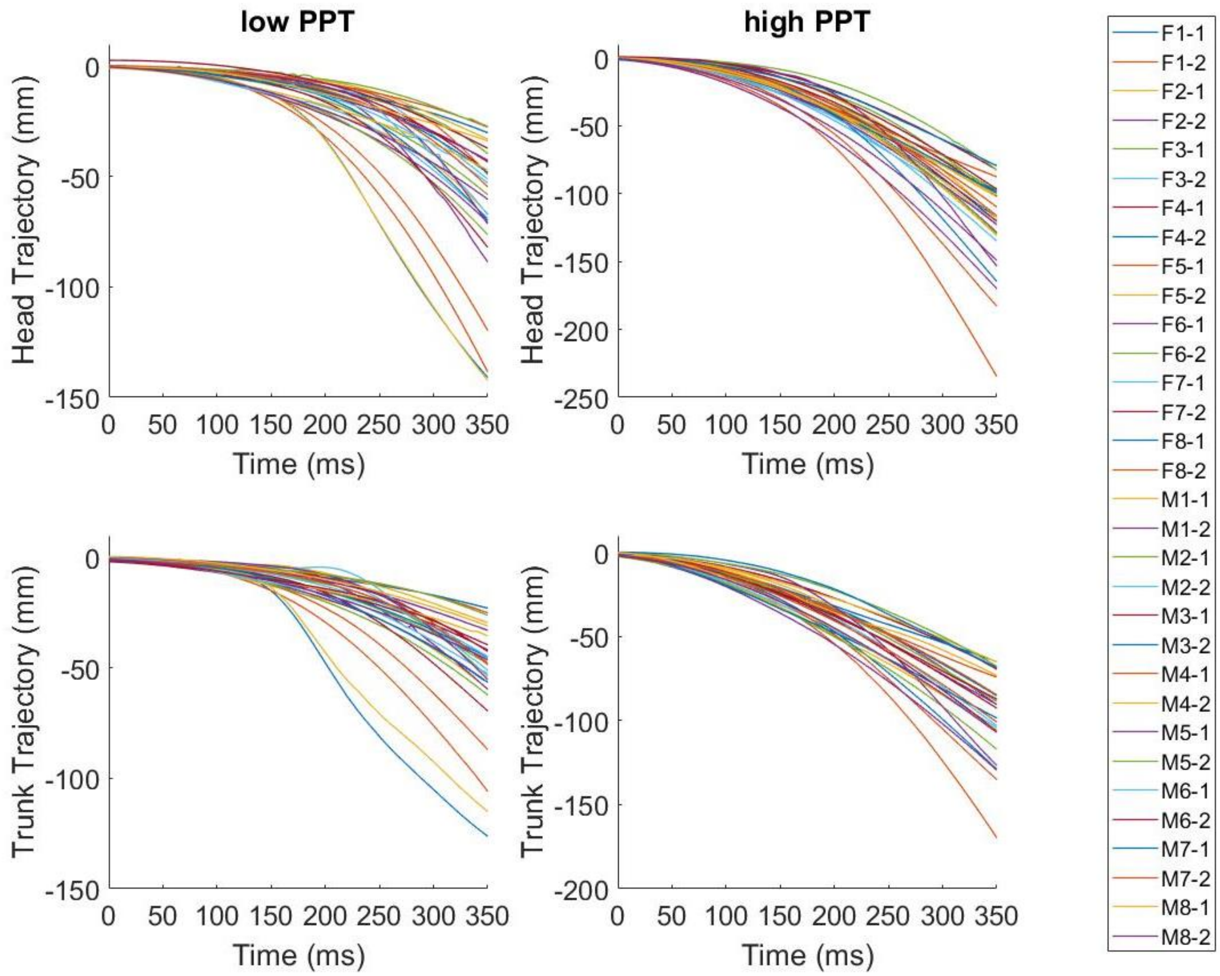

Figure 2. Head and trunk displacements from initial position in the low and high PPT conditions within 350 ms from the PPT onset for each participant trial.

There were no significant differences for Sex, PPT and Repetitions in the muscle activation ($p > 0.05$) except for the right bicep. The right bicep showed a statistically significant interaction between Sex and Repetition ($p>0.001$), showing that the males had greater bicep activation in the second repetition ($p < 0.004$). Overall muscle activation was the greatest in the sternocleidomastoid (SCM), trapezius and the rectus femoris, all other examined muscle showed activation equal or less than 7% of MVIC (Table 4).

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Table 4: Overall percent of muscle activation

Muscle	Right side (%MVIC)	Left side (%MVIC)
Bicep	3.0 ± 3.7	3.4 ± 4.3
Brachioradialis	6.6 ± 9.0	4.6 ± 8.6
Deltoid	5.0 ± 4.0	4.6 ± 4.4
Sternocleidomastoid	19.2 ± 22.4	19.3 ± 37.1
Trapezius	25.1 ± 26.5	16.3 ± 11.3
Rectus Femoris	23.6 ± 34.8	13.7 ± 14.4
Tibialis Anterior	4.1 ± 3.9	4.3 ± 6.0

The shoulder seatbelt load showed a statistically significant effect of repetition ($p < 0.001$): in the first repetition the shoulder belt load (112.2 ± 41.1 N) was greater than in the second repetition (88.4 ± 30.7 N).

DISCUSSION

The high PPT (300 N) condition in our study resulted in greater rearward motion (up to 175 mm) compared to the low PPT (100 N) condition (up to 110 mm). It is plausible that 300 N of force may not be necessary when occupants are not experiencing a pre-crash maneuver, as our findings show that a low PPT force of 100 N can successfully reduce out-of-position in static conditions. In static conditions, there is no critical timing for the subject to return to the optimal position within the seatbelt, as static conditions represent cases in which a vehicle travels with a constant speed (no changes in acceleration). However, timing becomes crucial in the presence of pre-crash maneuvers that occur in matter of milliseconds or seconds, so speculatively it may be necessary to use a higher PPT force level to reduce out-of-position in those cases (Graci et al., 2022, Mishra et al., 2023).

In our study we found substantial inter-subject variability in head and trunk motion (Figure 2), reaching a range up to of 100 mm, even though each participant was exposed to the same PPT conditions. Our occupant sample was relatively homogeneous in term of anthropometrics, as all participants were around the 50th percentile for height and weight for their age and sex group. Therefore, the inter-subject variability found in our study was potentially due to differences in occupants' behavior rather than size. This finding is line with the findings from a previous study conducted in forward leaning occupants being repositioned by a pretensioner (Hellenbrand et al., 2023). The authors found that after 160-180 ms from the pretensioner onset, the correlation between body size and rearward motion decreased as variability of behavior/posture emerged. In our study we purposely examined 350 ms after the PPT as we used a very tight range of anthropometrics, and we were interested in understanding the differences in rearward motion that

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emerge from different behaviors among occupants. Our findings on the inter-subject variability suggests that one size does not fit all for PPT force level and repositioning vehicle occupants may require careful fine-tuning of force level that considers factors beyond anthropometrics.

The activation of the PPT at any force level in static condition did not show to be associated with high muscle activation in our subjects: overall muscle activation was lower or equal to 25% of MVIC and no differences between force levels was found. These findings suggest that overall, occupants relied on a passive repositioning strategy (i.e., the PPT) rather than actively moving rearward (i.e., subjects contracting their muscle to initiate the rearward movement). In our study, we did not give instructions to the subjects on what to do when the PPT triggered, but rather we just instructed them to sit and relax. The presence of very small muscle activation during the PPT conditions reflects that the occupants followed the instructions and did not anticipate the PPT motion. Therefore, these findings may reflect realistic in-vehicle scenarios where the PPT is activated without the occupant expecting it.

Although muscle activation was small overall, three muscles showed between 13-25% of MVIC activation: the SMCs, the trapezii, and the rectus femoris. This finding suggests that these muscles may be the one mainly responsible for aiding the PPT in repositioning the head and trunk to an upright position from a forward leaning posture. However, it is also plausible that other muscles, that could not be detected with surface EMG, contributed to head and trunk rearward motion in our study.

Previously, it was found that SCMs, trapezii, and rectus femoris were active during evasive swerving maneuvers (Graci et al., 2022b, Holt et al., 2020, Ghaffari et al., 2021, Mathews et al., 2013). This suggests that these specific muscles were active regardless of the direction or intensity of a perturbation. It is worth highlighting that the same muscles (SMCs, trapezii, and rectus femoris) were also active when the same PPT force levels were examined under the same experimental conditions and occupants but during a simulated low-speed impact (Graci et al., 2022b). This finding supports the interpretation that the SMCs, the trapezii, and the rectus femoris are muscles influenced by the presence of the PPT itself rather than the change in acceleration, since they were also active when the PPT was present in static conditions. On the other hand, the magnitude of the muscle activation may be linked to the severity of the loading conditions. The activation of the SCMs across both dynamic (Graci et al., 2022b, Holt et al., 2020, Ghaffari et al., 2021, Mathews et al., 2013) and static conditions (the current study) may reveal that the subjects may also have equally experienced the startle reflex (Mang et al., 2012) across the two studies due to the surprise effect of the PPT in our study and the PPT and the pre-crash maneuver in our previous study.

The shoulder belt loads did not show differences between the two PPT force levels. We expected the shoulder belt load would be greater with the high force PPT compared to the low force PPT. We hypothesized that the occupants would contract their muscles less with the high force PPT compared to the low force PPT, as the high force PPT would do more work in

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repositioning the subject rearward. Previous studies found that greater seat belt load activation was accompanied by lower muscle activation and vice versa, particularly when the occupants experienced the PPT (Graci et al., 2022b, Holt et al., 2020) or were unaware of an impending pre-crash maneuver (Berkery et al., 2024). The lack of this relationship between seatbelt loads and muscle activations in our study could be because our subjects experienced the PPT in static conditions rather than in a pre-crash maneuver.

This study included some limitations. This study focused only on two PPT force levels (100 N and 300 N). Future studies are needed to identify PPT force level thresholds on different occupant populations. The laboratory environment is not a naturalistic vehicle on-road scenario. However, in our study we used a vehicle seat, and we mimicked the interior of a vehicle occupant compartment. The study was also completed with only one type of vehicle seat: although different vehicle geometries could lead to different magnitude of rearward motion, it is plausible that the differences in head and trunk motion between PPT conditions would stay the same across different vehicles seats.

CONCLUSIONS

Forward leaning occupants can be repositioned rearward up to 175 mm in 350 ms with a 300 N PPT in static conditions (i.e., when a vehicle travels at constant speed). Triggering the PPT prior to a pre-crash scenario, when the occupant is in an extreme out-of-position posture, could be beneficial as it could reduce the PPT force needed to reposition occupants in case a pre-crash maneuver occurs. Although no sex differences were found, likely due to height and weight similarities in our sample size we found there was inter-subject variability in head and trunk kinematics during the repositioning motion. This finding suggests that the PPT triggering, timing and force level might not be designed as one-size-fits-all and should consider not only occupant size but also behavior.

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