The Impact of Seat Belt Pretensioner Deployment on Forward Leaning Occupants

Ciboney Hellenbrand, J. Fletcher Brown, Adam Goodworth
Department of Kinesiology, Westmont College

ABSTRACT
Pyrotechnic seat belt pretensioners typically remove 8-15 cm of belt slack and help couple an occupant to the seat. Our study investigated pretensioner deployment on forward leaning, live volunteers. The forward leaning position was chosen because research indicates that passengers frequently depart from a standard sitting position. Characteristics of the 3D kinematics of forward leaning volunteers following pretensioner deployment determines if body size is correlated with subject response. Nine adult subjects (three female), ages 18-43 yrs old, across a wide range of body sizes (50kg-120kg) were tested. The age was limited to young, active adults as pyrotechnic pretensioners can deliver a notable force to the trunk. Subjects assumed a forward-leaning position, with 26 cm between C7 and the headrest, in a laboratory setting that replicated the passenger seat of a vehicle. At an unexpected time, the pretensioner was deployed. 3D kinematics were measured through a 9-camera motion capture system with reflective markers on the left and right glabella, tragus, manubrium, C7, lateral proximal head of humerus, olecranon process, patella, and lateral malleolus. For uniformity, all pretensioners were of the same model made by Autoliv and were dual systems (having deployment in the retractor and outbound anchor). The initial velocity of the trunk (first 50 ms) was dependent on the body size, with smaller subjects getting pulled back quicker. Following the first ~160 ms, there was a slight rebound where subjects briefly moved forward, followed by a period of high inter-subject variance in movement. By isolating the effects of pyrotechnic pretensioner deployment on live volunteers, this study fills in an important gap in automotive safety research and may help with evaluating computer models or designing future restraint systems with advanced sensor technology where pretensioners deploy prior to significant vehicle deceleration.

INTRODUCTION
Seat belt pretensioners are important safety devices designed to optimize the effectiveness of seat belts (Kahane 2013). Seat belt pretensioners are currently installed on nearly all vehicles and, when deployed through a pyrotechnic mechanism, remove about 8-15cm of slack in the belt. A dual pretensioner is common, which includes deployment in the retractor and the outboard anchor or buckle. Figure 1 shows a photo of a dual pretensioner before and after deployment.
A pretensioner is generally deployed when crash severity exceeds a certain threshold, similar to airbag deployments. The design of timing, force, and slack removal in pretensioners are largely performed in conjunction with results from crash tests with anthropometric test devices (ATD’s) sitting in a standard upright position. Prior research with pyrotechnic seatbelt pretensioners has shown the kinematic responses in cadavers (Foster et al. 2006) and ATD’s (Bohman & Fredriksson 2014), but we are unaware of any research evaluating the kinematics of live humans following pyrotechnic pretensioner deployment. In addition, human behavior and ATD responses are not identical, and humans may adopt a variety of non-standard sitting postures, especially as a passenger. Prior research shows that occupant positions often include slouching, a reclined seat, leaning forward, placing feet on the dash, etc. (Charlton et al. 2010, Goodworth et al., 2021). Occupants are also often rotated to one side or are interacting with their phone (Reed et al. 2019). Importantly, non-standard postures are often associated with increased injury risk (Bose et. al., 2010; Viano et al. 2009; Donlon et al. 2000; Dissanaike et al. 2008). Thus, a better understanding of how seat belts and pretensioners interact with non-standard sitting is important. Therefore, the current study investigates the interaction of pretensioners on live humans in non-standard sitting.

One recent study (Deleveet et al. 2013), presented at the Injury Biomechanics Symposium, investigated the effectiveness of a mechanical (non-pyrotechnic) pre-pretensioner on live humans adopting a non-standard (forward leaning) posture. This previous study addressed important questions about the future possibility of using a mechanical pretensioner. But, unlike standard
pyrotechnic pretensioners, mechanical pretensioners are not typically part of current seat belts and pull out slack with less force and speed. Thus, it is also valuable to consider the interaction of currently installed pyrotechnic pretensioners on non-standing sitting.

Our study describes subjects’ trunk, head, and shoulder responses to deployment of a pyrotechnic pretensioner when leaning forward and explores the relation between response magnitude and body size. This study may help future efforts to use pretensioners to reposition an occupant very early in a crash event. This is particularly important when considering the risk of an airbag expanding into an occupant who is not optimally positioned. Our study may also help investigators better understand the impact of pretensioner deployment on occupant kinematics in situations with forward leaning. Finally, a better understanding of occupant responses may help calibrate crash test models for computer simulations and give insights for restraint systems in autonomous vehicles where passengers could have more freedom to adopt a variety of sitting positions (McMurry et al. 2018).

METHODS

Test environment. Experiments were conducted in the Biomechanics and Balance Lab at Westmont College. A car seat was mounted to an aluminum structure that allowed for adjustment of the belt position to suit each individual (Figure 2).

![Figure 2. Subject and Experimental Setup. Subject is leaning forward (26 cm of C7 relative to the seat back) with reflective markers placed on the left and right glabella, tragus, manubrium, C7, lateral proximal head of humerus, olecranon process, patella, and lateral malleolus, the seat belt buckle, lower outboard and on the seat belt 13 and 18 cm from the D-Ring.](image-url)
Human subjects. Nine adult subjects (three female) ages 18-43 yrs. old across a wide range of body sizes (50kg-120kg) were tested. The age was limited to young active adults because pyrotechnic pretensioners can deliver a notable force to the trunk. This protocol was reviewed and approved by the Institutional Review Board (IRB) at Westmont College. To ensure full knowledge of the experiment, prior to testing, subjects were shown a video of a pretensioner deployment on a forward leaning human and informed of the procedure. Subjects’ height, weight, leg length (ground to ASIS) and torso length (ASIS to top of head) were also taken and recorded.

Protocol. Subjects wore shorts and tight cotton T-shirts to ensure similar friction across subjects when the seat belt retracted. Subjects were also given safety glasses and earplugs to account for the loud noise from the pretensioner deployment. Subjects were asked to place the seat belt on in their typical manner. Researchers then checked to be sure the lap belt was under the pelvis ASIS and the shoulder belt ran across the clavicle. When subjects were sitting in a normal, upright position against the seat back (prior to leaning forward), the D-ring was placed rearward of their right shoulder 18cm and above their shoulder 18cm. Then, the belt was locked and subjects leaned forward to measure their voluntary force onto the belt, as well as tighten any loose webbing (‘film spool’) that may have been present in the belt. Then, subjects were instructed to lean 26 cm forward, which was verified by measuring the distance between the subjects’ C7 marker and the seat. At a semi-unexpected time (within a ten second window), the pretensioner was deployed.

Seat belts. For uniformity, all pretensioners were made by Autoliv, fit the same model run, and were dual stage, having deployment in the retractor and outbound anchor.

Instrumentation & Data Processing. Kinematics was tracked using a 3D motion capture system with 9 cameras. Reflective markers were placed on the left and right glabella, tragus, manubrium, C7, lateral proximal head of the humerus, olecranon process, patella, lateral malleolus, the seat belt buckle, the lower outboard and on the seat belt 13 and 18 cm from the D-Ring toward the buckle. Seatbelt force output was recorded with a seat belt tension force sensor (Messring, 16kN max force). The sensor was placed between the 13 and 18 cm markers. These data were not collected consistently in all tests and are not included in the present study.

Data processing. All markers were labeled in Motive motion capture software and then exported and analyzed in MATLAB through custom programs (Figure 3). We calculated the displacement for C7, representing trunk movement from the initial forward lean; the head, which was an average of movement of the left tragus, right tragus, and glabella; and the left and right shoulders. The displacement data collected was analyzed primarily in the anterior-posterior direction because the pretensioner pulled back the body toward the seat primarily in the sagittal plane. The velocity (cm/s) of C7 was calculated during the initial period (about 160 ms) following the deployment. We also calculated the head angular rotation about C7. Kinematic data was filtered with a 20 Hz low pass filter.
Figure 3. Reconstruction of 3D markers in MATLAB showing various time points of markers (circles) following the deployment. The primary markers of interest were C7, shoulders, and head. The head was defined as the average across the right tragus, left tragus, and glabella.

RESULTS

Because the seat belt pretensioner applied a direct force to the trunk, we first describe results of trunk kinematics, followed by head kinematics, and then summarize kinematic responses across other body segments.

Trunk kinematics. Figure 4 shows the trunk responses for all subjects (left) and the average subject (right). For the average subject, we divided the trunk responses into 3 phases following the deployment at time zero. In phase one, for approximately 160 ms following deployment, the trunk was pulled backward and toward the seat until reaching a local minimum. Some subjects reached this minimum in 120 ms, while others took 180 ms; and the positions the local minimum ranged from 4.6 cm to 8.1 cm relative to the starting forward leaning position. This first phase was the most consistent amongst subjects.
Figure 4. Trunk displacement measured at C7 following pretensioner deployment at time=0s. The trunk was pulled backwards and toward the seat (negative vertical axis) from the starting, forward leaning position (0 on the vertical axis). On the left plot, each line represents one of the 9 subjects. On the right, the bold blue line is the average trunk position across subjects, with one standard deviation across subjects represented by the two gray lines.

In the second phase, the trunk recoiled forward (away from the seat) briefly to a local maximum. Phase 2 is the time period from the first local minimum to first local maximum. This forward movement period lasted around 120 ms for the average subject. Phase 3, which occurs around 280 ms following deployment, consists of a wide range of movements across the nine subjects. As seen in figure 4, in the left plot, the direction and magnitude of these movements varied widely, reaching a position of between 2.5 and 22.3 cm backward from the starting position. Some subjects moved farther backward, while others moved slightly forward during phase 3.

Head displacement. The head displacement was similar to the trunk. Most subjects' head movement was around 5 cm backward during phase 1, followed by a 0.3 to 7 cm recoil forward (away from the seat) during phase 2. Like C7, head displacement during phase 3 had high inter-subject variance.

Head rotation. Figure 5 shows head rotation about C7 relative to its starting angle at the beginning of the test. Positive numbers are flexion. Initially following deployment, head flexion was present amongst all subjects. The average peak head flexion was approximately 15 degrees.
and this peak occurred at about 70 ms following deployment. Following this peak head flexion, the head moved toward backward relative to C7 (reducing the flexion). As time progressed, head rotation because less consistent across subjects and move variable. By 1.6 s, the standard deviation in head rotation ranged from 8 degrees of flexion to 27 degrees of extension.

Figure 5. The average head rotation (Movement of the head in the sagittal plane about the fulcrum C7) following pretensioner deployment at time = 0s. The head was forced into an initial flexion (positive) relative to its starting orientation (0 value on vertical axis) followed by extension at later time periods (negative values on the vertical axis). The bold, blue line represents the average subject with 1 standard deviation across subjects as the two gray lines.

Subject Movement as Correlated to Subject Size. To examine correlations, phase 1 was examined in more detail. Two distinct subphases were evident, each with a clear and separate velocity. The first subphase lasted 50 ms following deployment. During these 50 ms, C7 velocity showed an inverse relationship between the subject’s body mass. Larger subjects had smaller velocity, while smaller subjects tended to have larger velocity. Figure 6 shows this correlation, which had an R value of 0.91 and a p value of 0.0019. Note, one subject who was an obvious outlier (6 standard deviations away from average model fit) was removed from this analysis.
As time progressed following the deployment, correlations with body size decreased. Between 50ms and 160ms, there was still a negative association between body size and velocity, but the R value dropped to 0.49. Metrics of position in later periods (phases 2 and 3) were not noticeably correlated with body size.

**Additional kinematics and trunk rotation.** Because the shoulder harness pulled more directly on the right shoulder, we examined if any asymmetry existed between shoulders. Figure 7 shows a top-down (transverse plane) view of the two shoulder markers averaged across subjects. Initially, both shoulders were aligned. Following deployment, the right was pulled backwards nearly 5cm more than the left shoulder during the first initial negative peak (first local minimum in the right plot). Both shoulders exhibited a similar rebound as C7, with a slight forward movement following the first backward pull.
Feedback from participants. Even after watching a video of the deployment on a sample subject, participants in our study reported the experience as sudden and surprising, but not painful. Several participants reported anxiety in the seconds leading up to the deployment.

DISCUSSION

Interpretation of kinematic responses. Following the deployment, the trunk was pulled back between a 4.6 and 8.1 cm, toward the seat for about 160 ms. We assume minimal muscle activation at the first start of the test as subjects were instructed to relax. Therefore, the initial trunk velocity was related to body size because a given force from deployment is proportional to mass and acceleration. The larger subjects moved backward initially with a slower velocity. We did note one subject who was an outlier who exhibited much lower velocity (more resistance to acceleration from the deployment). One explanation for this outlier is co-contraction, which is known to influence trunk stability and resist motion (Lee et al. 2006). Co-contraction could also play a role in car crashes if someone anticipates the accident (Bose et al. 2008).

Between 160-280ms, subjects exhibited a small rebound with forward velocity of the trunk. We propose two explanations for this finding. One explanation is that the springs in the chair and the backrest were compressed during the initial 160ms as the subjects moved into the seat. By compressing the springs, the spring stored energy and then released the energy slightly pushing the body forward. Consistent with the explanation, we found the rebound included an upward (vertical) displacement in addition to the forward displacement. An alternative explanation is that trunk muscle reflexes were triggered. Trunk muscle reflexes are often modeled as lasting 25-80 ms between stimulus and force generation (Shumway-Cook et al., 2023; Goodworth et al., 2009). We propose a future study could test ATDs to help distinguish between these explanations.
The third phase was the most variable across subjects. Some subjects moved backward over 20 cm while others resisted and moved toward their initial forward leaning posture. The time scale was past normal reflexive response ranges, so it was most likely that this was due to a conscience or subconscious behavior response of the subjects.

Comparison to other studies. The most similar previous study we found examined how a mechanical pre-pretensioner was able to pull back a forward leaning occupant (Develet et al. 2013). Live subjects were tested in a normal sitting position and two forward leaning positions (26 and 40 cm at T1 to seat). Their mechanical pretensioner pulled over a relatively long period of time with two peaks at 250 and 500 ms. The peak trunk position was 18 cm backward, which occurred at 550 ms during the 26 cm leaning test. In comparison, the pyrotechnic pretensioner in the present study deployed much faster (about 16 ms). Our subjects had smaller but much faster responses. By 550 ms, our subjects were in the third phase where responses varied widely (10 cm average). The peak head rotation was comparable in direction and magnitude between studies.

Implications. Isolating the effects of the pretensioner deployment on the occupant is relevant and important. First, as vehicles continue to progress in crash detection abilities, pretensioners will likely continue to be deployed earlier in the crash event and prior to significant inertial loading of the belt from vehicle deceleration. It is already evident from newer NCAP tests for NHTSA that pretensioners are deployed prior to notable forward movement of the occupant into the belt (eg, NCAP test number 11377.). With early deployment, it may be possible for pretensioners to safely reposition an occupant. Our results suggest that current pretensioner systems would quickly pull back subjects about 7cm in the first 160 ms. Thus, if someone was leaning forward 26 cm (C7), to fully reposition and provide a tight belt fit, an alternative system, such as a dual-stage system would be required to pull even more slack out of the belt. The current feasibility of this is not known. However, one theoretical study suggested that injuries would be reduced if future seating systems could detect sitting positions and adjust pretensioner and airbag deployment accordingly (Adam & Untaroiu 2011).

Finally, the detailed kinematics (head and trunk position and velocity) characteristics may be useful to calibrate modeling studies. Specifically, future computer simulations that include a forward leaning occupant with an early pretensioner deployment may benefit from the kinematics in the current study by validating the simulated responses to those obtained from live human testing.

Future steps. As noted above, testing of an ATD would help understand the role of a co-contraction, reflexes, and muscle responses. In addition, in our testing protocol, we had a belt force sensor and additional, alternate conditions on a subset of subjects, such as starting with the seat belt tightened vs. loosened. Future testing could include testing subjects in other non-nominal positions (like mimicking use of the radio with an inboard lean or sitting with feet on the seat). However, because of the notable forces involved, there are limitations in pretensioner testing on live subjects that likely preclude subjects like older adults, children, or pregnant

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women. As improved testing dummies and other simulation devices are created, there may be more options available for testing these common conditions and vulnerable populations.

CONCLUSION

Our study is the first to isolate and describe the effects of pretensioner deployment on live forward leaning subjects. In forward leaning passengers, pretensioner deployment pulled back the average subject 7 cm within 160 ms. The initial velocity of the trunk (first 50 ms) was dependent on the body size, with smaller subjects getting pulled back quicker.

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REFERENCES


