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Abstract: The objective of this study was to validate an indentor system—called a cushion loading indentor (CLI)—for use in objectively evaluating seat cushion performance for heavy truck seats. Included in this study is a detailed description of the five-component indentor design, with major components being a polyurethane buttocks mould and a variable weighting system. Validation of the CLI was performed by comparing its interface pressure distribution with five human test subjects for four different seating surfaces. The results demonstrate that the CLI is both more repeatable than the human test subjects and provides similar pressure distribution to that of a seated person. Furthermore, it is shown that the CLI is valid for dynamic testing of heavy truck seat cushions owing to the inclusion of the seat suspension, which significantly reduces the dynamic complexity between the cushion and the seated person.

Keywords: seat comfort, cushion loading indentor, ride comfort, seat cushion, truck seat, air-inflated cushion, air ride, heavy truck ride

1 INTRODUCTION

The short-term comfort offered by an automobile seat is relatively easy to determine by many measures, the most effective of which is a subjective evaluation that surveys potential users as they compare the relative 'feel' of different seat designs [**1**]. This practice is often adopted for different vehicles, ranging from passenger vehicles to commercial vehicles such as trucks, buses and off-road vehicles. The problem, however, with subjective evaluations is that they can be extremely costly and time consuming.

The process of performing a subjective evaluation includes gathering several test subjects of different height, weight, age, gender and race. These subjects must then be used to evaluate a particular seat and/or seat cushion in varying operational environments. Ultimately, these experiments must be conducted for many different seat designs in order to provide a source of comparison, because comfort is relative. The process becomes even more complicated because the individual subjective evaluation can be dependent on aspects not directly related to the seat such as age, gender, health, sensitivity, attitude and motivation [**2**].

To alleviate some of the inherent problems with the subjective evaluation, much research has been performed in recent years to find objective measures for predicting seat comfort [**2**–**7**]. Some of the proposed objective measures include vibration, interface pressure and anthropomorphic measurements. Fundamentally, the search for quantitative methods represents an attempt to understand the underlying causes of discomfort.

In order to obtain an objective measure of comfort, the experimental evaluation must include multiple objective measurements which must be correlated with subjective evaluation to determine their relationship, if any. Once an objective measure is found to be highly correlated with the subjective analysis it may then be considered a comfort metric. The benefit of the comfort metric is that now simple experiments—such as measuring vibration transmissibility and interface pressure—can be performed with the seat in question and a reasonable judgement can be made as to how much comfort it will provide, thus eliminating the subjective survey. Furthermore, if a reasonable mechanical model of the human body is constructed, the reliance on the human test subject no longer exists, thus eliminating inherent repeatability problems.

It is well known that the use of human subjects 'does not provide sufficiently repeatable results—even when using the same subject, instruments, and investigator' [**8**]. Specifically, repeated tests can show large variations in pressure measurement primarily as a result of undetected changes in posture.

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Consequently, the validity of using of a mechanical device to simulate a human test subject in evaluating vehicle seats and seat cushions with regards to pressure distribution is subject to the following two criteria:

1. It must provide similar pressure distribution to that of a seated person.
2. It must be more repeatable than the human test subject.

The purpose of this paper is to describe such a system—called a cushion loading indentor (CLI) for the purposes of this study—that will give highly repeatable results to allow for the comparison of different types of seat cushions based on objective comfort measures. This paper presents the results for the validation of the CLI using multiple types of truck seat cushions—specifically three different types of foam seat cushions and an air-inflated seat cushion.

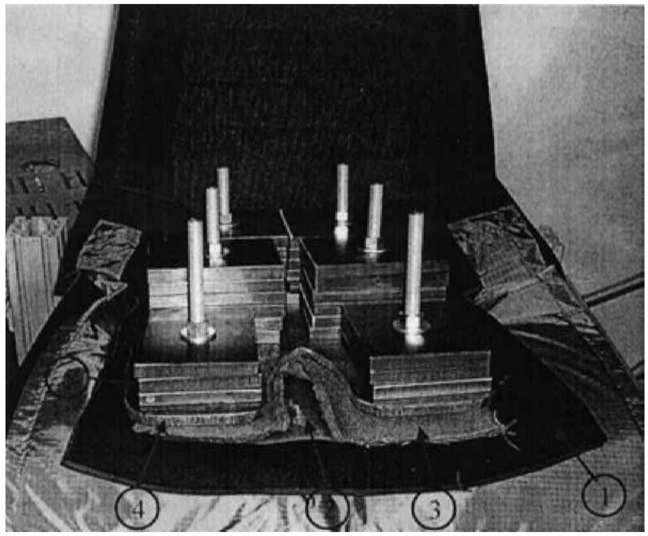

Fig. 2 CLI positioned on truck seat

2 CUSHION LOADING INDENTOR

The CLI was designed and built by the Advanced Vehicle Dynamics Laboratory (AVDL) at Virginia Tech for the purpose of researching comfort and long-term fatigue of a seated driver [**9**]. The main objective of the CLI system was to adequately simulate variable pressure distribution, similar to what would be attained by a seated person, in a repeatable manner. As highlighted in Fig. 1, the indentor system consists of the following five components:

(a) a 0.5 mm thin layer of neoprene;
(b) a human buttocks shaped polyurethane plastic mould;
(c) a soft weighting system;
(d) a base plate with loading rings;
(e) 3.5 in × 5 in weights for variable loading capability.

The indentor system is prepared, as shown in Fig. 2, by placing the 0.5 mm sheet sheet of neoprene directly onto the surface of the seat cushion. The neoprene is used specifically to simulate the resilience of human tissue. Placed on top of the neoprene is the human buttocks shaped polyurethane mould.

The mould is made of a 30 durometer polyurethane-based material (Poly 75-30) developed by Polytek Development Corporation [**10**]. The material was chosen for its compliance with different types of seat cushions. The mould was constructed by pouring the Poly 75-30 into a negative mould created from an average of 80 seated men of mass 200 lb. Two golf balls were placed inside the mould to simulate high pressure areas analogous to those areas created by the ischial tuberosities. On top of the mould is placed a soft weighting system used to fill voids between the mould and base plate that are created by the inherent contouring of the cushion. The base plate, which is instrumented with six weight-loading rings for repeatable loading, is then placed on top of the soft weight. The 3.5 in × 5 in weights—weighing approximately 2 lbf apiece—are then placed on the loading rings of the base plate and secured by a washer and nut. The user has the option of loading the base plate in any configuration necessary. In sitting, most of the weight is supported by the ischial tuberosities of the pelvis and their surrounding soft tissues. As shown in Fig. 3, the ischial tuberosities generally support around 45 per cent of a person's weight [**11**]. The individual loading weights allow for such a distribution.

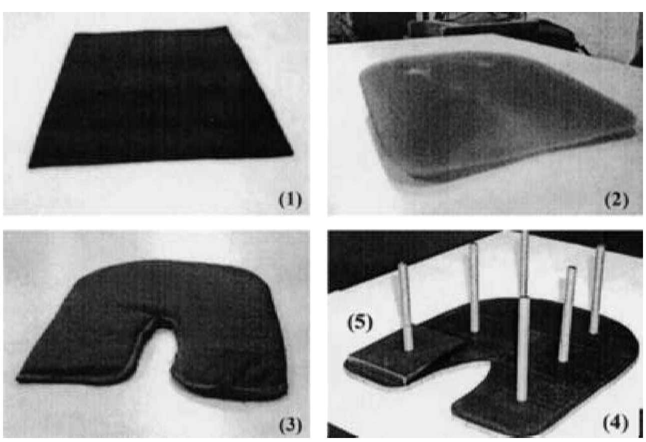

Fig. 1 Components of the CLI

3 TEST PROCEDURE

As previously mentioned, a CLI is only valid if it, in a repeatable manner, provides similar pressure distribution to that of a seated person. Therefore, in order to compare pressure distribution between the CLI and a seated person, the CLI and five human subjects were

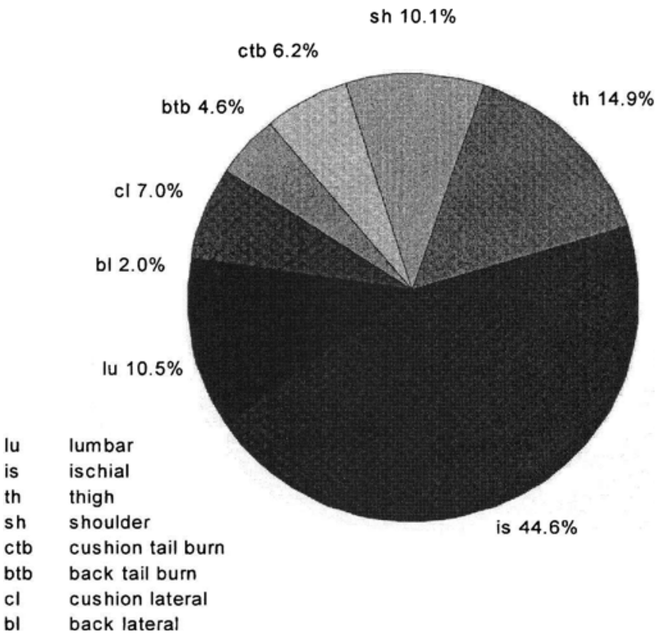

Fig. 3 Typical weight distribution when seated; reprinted from reference [**10**]

tested on three different types of foam seat cushion and an air-inflated cushion as described in Table 1. The five human test subjects were chosen to model the large variance in truck driver weight, height and build. To measure repeatability, the CLI was applied five times to each seat surface, and the human subjects sat five times in each seat. During each trial, the CLI was positioned similarly, while the human subjects attempted to sit repeatably in the same comfortable position.

Seat cushion interface pressure was measured using the Tekscan Body Pressure Measurement System (BPMS). This system uses a thin flexible resistivity-based sensor pad featuring a 42 by 48 array of individual 0.16 in^2 pressure-sensing elements [**12**]. Pressure data were saved in ASCII format using the Tekscan BPMS software and then converted to a format readable by Matlab. Post-processing of pressure data was then performed in Matlab. Sample pressure distributions for each of the five test subjects and the CLI are given in Fig. 4.

For each human trial, the BPMS pressure pad was placed over the surface of the seat in question. The subject was then instructed to sit down in a comfortable seated position, with their hands in their lap and feet squarely on the floor. A snapshot of the pressure distribution was recorded, and the subject was instructed to stand up. The test subject then returned to the same seated position. The procedure for each CLI trial was identical in that the CLI was set up—as described in the previous section—on the seat surface and removed for each test.

Table 1 Description of test seat cushions

Seat cushion	Description
S1	Low profile polyurethane foam base with a polyester cloth cover
S2	Highly contoured polyurethane foam base with a polyester cloth cover
S3	Neoprene-based air-inflated seat cushion made of interconnected air cells with stretch cloth cover
S4	Orthotic urethane foam based seat cushion with no cover

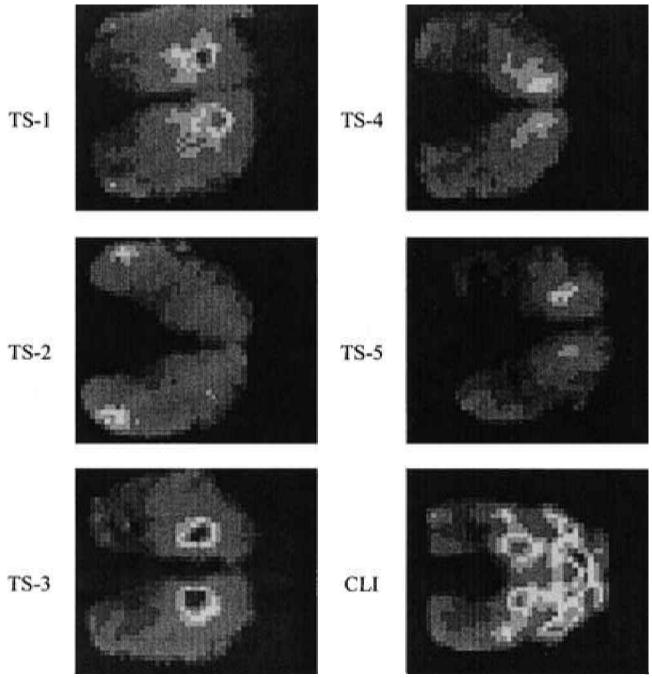

Fig. 4 Sample interface pressure distributions of the CLI and five test subjects

4 RESULTS AND DISCUSSION

The experimental results are focused on validating the CLI by first showing that it provides a similar pressure distribution to that of a seated human subject and, secondly, by showing that it is more repeatable than the human test subject. The method of validation includes comparisons of peak pressure, standard deviation, average contact pressure and contact area. Subsequent discussion deals with the aspects of using the CLI to evaluate truck seat cushions in a dynamic environment.

4.1 CLI validation using pressure distribution

The results shown in Fig. 5 are the interface pressure distributions—displayed in the form of standard deviation—of each of the five test subjects and the CLI. The pressure distributions are presented as an average of the five repeated tests. That is, a standard deviation was calculated for each of the five recorded pressure maps

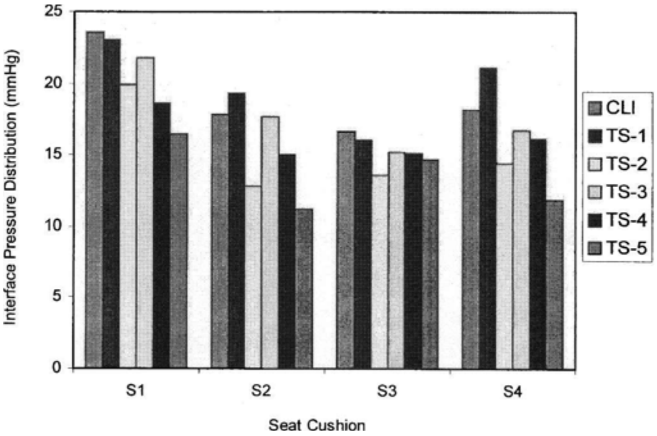

Fig. 5 Standard deviation of the interface pressure distribution over the Tekscan pressure pad for the CLI and five human test subjects

and the average of those five values was taken as the averaged pressure distribution.

The results demonstrate that the CLI has a similar pressure distribution to the human test subjects for various seating surfaces. The CLI pressure distribution most closely agrees with subject 1 (TS-1) owing to the similar seated weight. Seated weight refers to the total weight as seen by the pressure pad. The seated weight of the CLI was approximately 140 lbf while test subject 1 had a seated weight of approximately 155 lbf. It is worth again noting that the CLI is equipped with a variable loading system that allows the weight to be increased or decreased and distributed in any manner necessary.

The second goal of the pressure distribution validation was to show that the CLI is more repeatable than the human test subject. Figures 6 to 8 present the repeatability of the CLI and the five human test subjects in the form of average pressure, contact area and peak pressure. The peak pressure was taken as the highest pressure

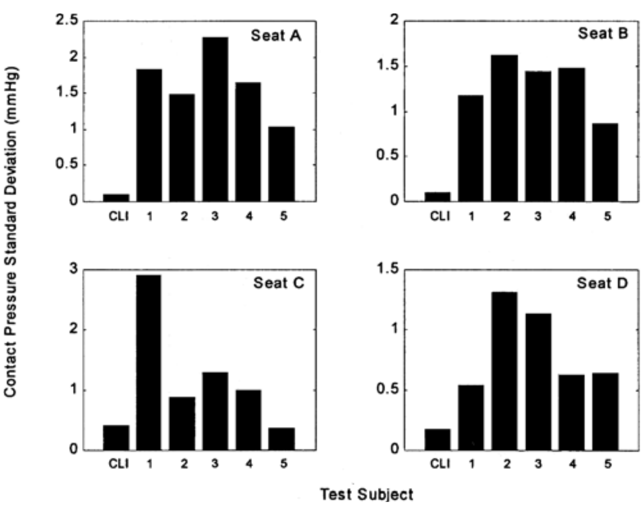

Fig. 6 Comparison of the repeatability of CLI and human test subjects over five repeated tests, presented as a standard deviation of the average contact pressure

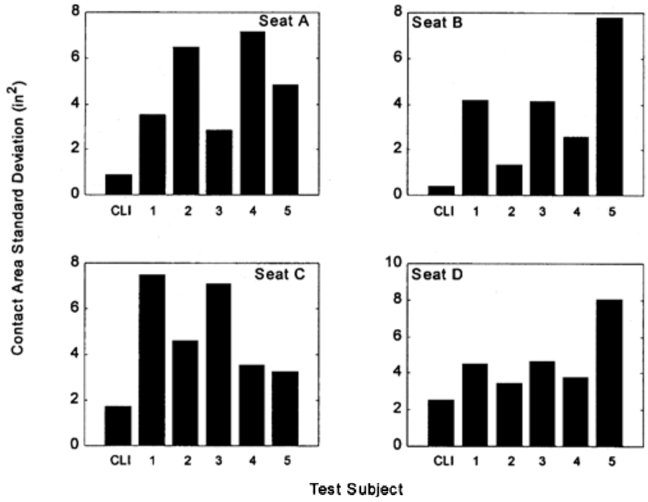

Fig. 7 Comparison of the repeatability of CLI and human test subjects over five repeated tests, presented as a standard deviation of the total contact area

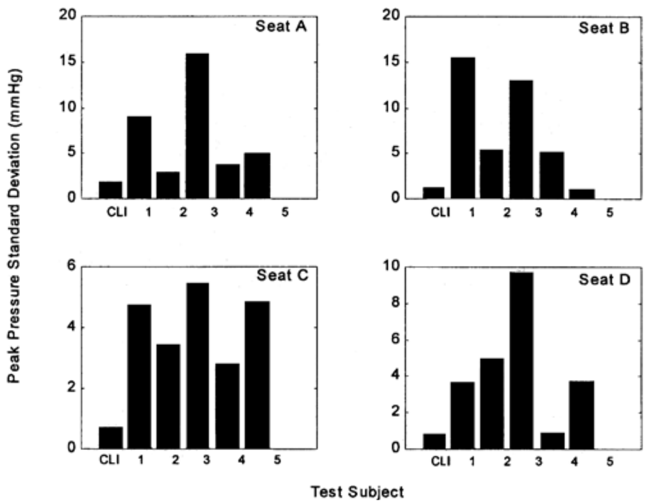

Fig. 8 Comparison of the repeatability of CLI and human test subjects over five repeated tests, presented as a standard deviation of the peak contact pressure

reading from the pressure pad's 42 by 48 array of individual 0.16 in^2 pressure-sensing elements. The results were determined by measuring the change in the average pressure, contact area and peak pressure throughout the five tests, for the CLI and the five test subjects. The results are presented in the form of a standard deviation.

The results show that the CLI is much more repeatable than the human test subjects for measuring average contact pressure, contact area and peak pressure. In many instances, the CLI exhibits repeatability improvements that are an order of magnitude better that the human test subject. The advantage with the CLI is that simple measurements can be made to place the CLI in the same position on the truck seat each time. With the human test subjects, even when measurements are made, there are subtle, undetected changes in posture that greatly affect the repeatability from one test to the next.

4.2 CLI dynamic considerations

It is acknowledged that the dynamic behaviour of the human body is sufficiently complicated that it cannot be simulated with a rigid mass or even a more complicated fabrication, such as a manikin [13]. This problem, however, is alleviated considerably when evaluating seat cushions for the typical heavy truck because of the addition of the seat suspension—typically referred to as 'air ride'.

As shown in Fig. 9, the vertical natural resonance frequency for a typical foam and metal spring seat is around 4 Hz, with additional amplification up to approximately 6 Hz. This frequency spectrum is very important because the spine, shoulders and head resonate in this frequency range [14]. As a result, resonance of the human body creates a much more complicated interaction between the interface of the seated person and seat cushion, which is the focus of experimentation. Addition of seat suspension in a truck seat, however, has been shown to lower its vertical resonant frequency to approximately 1.5 Hz as well as to lower the magnitude of transmission to approximately 2 Hz [15]. This reduction in vibration transmission is considerable because of the avoidance of the many human resonant frequencies above 2 Hz—specifically in the 4–8 Hz range. Therefore, without these additional dynamics, the interaction between the cushion and the seated person is significantly less complicated and thus can be modelled with the CLI.

The other consideration that remains is whether the CLI accurately simulates the human buttocks with regard to the subtle changes that occur at the seat cushion interface, such as tissue deformation. Although the combination of the neoprene layer and the polyurethane buttocks mould does provide deformation, it does not exactly imitate the complexities of human tissue. It must be remembered, however, that the CLI was not created to replicate exactly the interconnected behaviour of human buttocks tissue and underlying skeletal structure with the seat cushion but to have the ability to analyse fundamental differences in the performance of very dissimilar types of seat cushions (e.g. foam and air-inflated seat cushions).

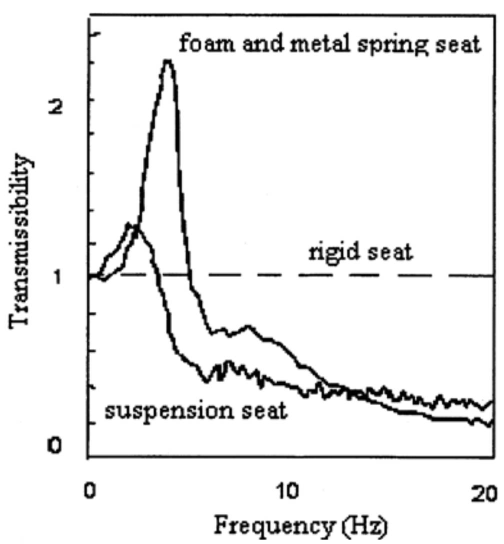

Fig. 9 Effects of air ride suspension; adapted from reference [15]

5 CONCLUSIONS

The intention of this study was to describe and validate a CLI system for objectively evaluating different types of heavy truck seat cushions. The main components of the CLI are a human buttocks shaped, durometer 30, polyurethane mould and a variable weighting system.

Validation of the CLI was performed in two parts. The first part compared the interface pressure distribution between the CLI and five human test subjects when seated on four different types of seating surfaces. The five human test subjects were chosen to model the large variance in truck driver weight, height and build. The second part compared the repeatability of the CLI with that of the human test subjects. Average contact pressure, contact area and peak pressure were all used to measure repeatability from one experiment to the next.

The results showed that the CLI has a similar pressure distribution to the human test subjects for various seating surfaces and is more repeatable. The pressure distribution of the CLI was most comparable with the test subject with a similar seated weight. This result is encouraging because it shows that the CLI can be used to model the interface pressure distribution of both lighter and heavier individuals. Furthermore, the increased repeatability of the CLI relative to the human test subjects allows for the objective evaluation of seat cushions without the need to consider the effects of changing posture.

Consideration of the CLI for use in a dynamic environment becomes acceptable when experimenting with heavy truck seats, owing to the seat suspension. The addition of the seat suspension significantly reduces the amount of vibration energy that is transmitted to the human body in the critical 4–8 Hz frequency range, which considerably lessens the dynamic complexity between the cushion and the seated person. Therefore, without these additional dynamics, the CLI—a more concentrated mass with variable pressure distribution similar to a seated person—may be used to examine the fundamental differences in the performance of dissimilar types of seat cushions, such as foam and air-inflated seat cushions.

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