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Verification of seat effective amplitude transmissibility (SEAT) value as a reliable metric to predict dynamic seat comfort

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Abstract

A rough road vibration stimulus was reconstructed on a shaker platform to verify if seat effective amplitude transmissibility (SEAT) values can be used as a reliable metric to determine dynamic seat comfort using seven seats and six subjects. The virtual seat method was combined with a paired comparison procedure to obtain reliable subjective dynamic seat comfort data. The psychometric method of constants, a 1-up-1-down Levitt procedure and a 2-up-1-down Levitt procedure were compared experimentally to find the most accurate and efficient paired comparison scheme. A two-track, interleaved, 2-up-1-down Levitt procedure was used for the subjective dynamic seat comfort assessment. SEAT value is an objective metric and has been widely used to determine seat vibration isolation efficiency. There was excellent correlation ($R^2 = 0.97$) between the subjective ratings and estimated SEAT values on the seat-top when the values are averaged over the six subjects. This study suggests that SEAT values, estimated from averaged seat-top transmissibility functions of six carefully selected subjects, could be used as a reliable metric to select the best seat for a specific road vibration input.

1. Introduction

Vehicle purchases are driven by consumer requirements such as functionality, safety, luxury, comfort, cost and performance. The consumers' perspectives on the fulfilment of these requirements are often based on subjective perceptions. With the increasing sophistication of the automotive industry and tough competition among the different manufacturers, it is likely that vehicles, which best satisfy these requirements and create the perception of doing so, will be the best sellers and hence more profitable for the automotive manufacturers.

Passenger seat comfort depends on both static and dynamic comfort. Static comfort refers to the comfort of the vehicle occupants when the vehicle is stationary such as when a prospective client is seated in a vehicle on the showroom floor. The static comfort experience includes everything from the visual impression of the styling to the smell and tactile experience when sitting in the seat. A statically comfortable seat requires the minimum muscular effort from the occupant to maintain the seated position. This implies that muscular fatigue is minimised because the body is sufficiently supported by its contact with the seat, seatback and floor [1].

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Dynamic comfort is mostly characterised by the noise, vibration and harshness (NVH) attributes when the vehicle is driven. The interior sound of the passenger's compartment has become increasingly important as automotive manufacturers strive to improve brand identity, customer loyalty, and perceived quality of their products [2]. Noise and vibration are intricately linked as vibration can cause noise and vice versa.

Most of the vibration experienced by occupants in a vehicle is transmitted to the body through the seat. The vibration environment, the seat dynamic response and the response of the human body to vibration combine to determine the seat's dynamic comfort. The optimum seat is one that minimises unwanted vibration responses of the occupant in the relevant vibration environment [1].

Dynamic comfort is usually assessed by making vibration measurements on the top of car seats using methods based on ISO 2631:1997 and other national standards [3]. This is done using a seat-pad accelerometer that measures the vibration at the seat occupant interface. Therefore, the question arises as to which vibration measurements do in fact assess occupant perception of dynamic seat comfort and correlates the best with subjective assessments.

To date various metrics and weighting functions have been proposed to establish a relationship between objective vibration measurements and subjective perceptions thereof. One of the earliest was by Pradko and Lee [4], who postulated that the power absorbed by the human is a good indication of both comfort and fatigue due to vibration exposure on a seat. In a later study by Varterasian [5], the correlation between objective vibration measures and subjective human evaluation thereof was reported. In this study up to 16 subjects were asked to evaluate the comfort of six seats by directly comparing the ride on a pair of seats attached to a shaker and then choosing the most comfortable one. The objective measures consisted of the weighted root mean square (rms) acceleration measured at the seat-top for a specific vibration input at the base of the seat according to ISO 2631 (1976) [6] and an empirically derived ride number. It was shown that in 60% of the cases the subjective choices of the occupants correlated with the ISO 2631 (1976) comfort criteria and if some seats, which had near identical dynamics, were removed the agreement increased to 65%. Using the ride number, R, the results improved to an agreement of 67% for all seats and 80% if only bucket seats were considered.

Currently, the most popular method used to evaluate dynamic seat comfort is the seat effective amplitude transmissibility (SEAT) value. This value can be calculated directly from measured data obtained by driving a vehicle on a test track or in a laboratory where a man-rated shaker [7,8] is used to induce the base excitation. In addition, SEAT values can be calculated from experimentally obtained seat transmissibility functions for a variety of vibration input spectra. It is defined as the ratio of the vibration on the seat and the vibration on the floor and accounts for human sensitivity to vibration [9]. SEAT value is defined as

$$\mathrm{SEAT\%} = \frac{\text{Vibration on the seat}}{\text{Vibration on the floor}} \times 100, \tag{1}$$

where *Vibration on the seat* and *Vibration on the floor* can be represented by the rms or vibration dose value (VDV) of the measured signals. As the human-seat system frequently exhibit nonlinear behaviour one should be careful when interpreting SEAT values. It is not possible to compare SEAT values without taking into account the vibration input, the level of the vibration and the physical characteristics of the seat occupant.

Van Niekerk et al. [10] successfully correlated the subjective dynamic seat comfort experiences of six subjects and 16 seats with SEAT values on the seat-top for a single rough road stimulus with the rigid body dynamics of the vehicle filtered out. The goal of this research was to further investigate the promising results of Van Niekerk et al. [10] and to correlate the subjective dynamic seat comfort response with SEAT values for a different vertical road vibration stimulus which included the rigid modes as well as different spectral content. Such a correlation would support the practice of predicting subjective dynamic seat comfort perception using SEAT values. This would provide vehicle design teams with an effortless method to choose a seat that is dynamically the most comfortable for a specific application.

Subjective testing includes the application of a procedure referred to as "comparison of stimulus pairs" [11]. This method eliminates the time lag between the comparison of two seats and human bias due to static comfort. Each trial in a paired comparison test consists of two vibration stimuli. During each trial the subject is asked to choose the more comfortable of the two stimuli. Through methods described in this text, the paired comparison test results in a subjective seat comfort rating. When the seat comfort ratings are combined they result in a subjective dynamic seat comfort assessment.

The objective dynamic seat comfort assessment includes the calculation of SEAT values. These values can be calculated directly from vibration measurements on the seat-top and floor or indirectly by estimating the vibration on the seat-top from the seat transmissibility function. Low SEAT values indicate a good seat, whereas high SEAT values indicate a bad seat.

It is possible to measure or estimate SEAT values in a number of different ways. Firstly, it is possible to use measured vibration data directly which is obtained when a person on a seat is exposed to a specific vibration input in a vehicle, by driving at constant speed over a repeatable road surface, or on a man rated shaker, which can safely be used with human subjects, using synthetic or actual measured vibration input at the seat rails. Depending on the characteristics of the vibration it is possible to use either the weighted rms value of the signal, or, if there are significant transient peaks in the measured signals it is more appropriate to use the VDV. If data with low crest factors, typically less than nine, are being analysed it is sufficient to use the weighted rms values to calculate the SEAT values. The crest factor is the ratio of the peak amplitude to rms value for the data, and is a measure of how ‘‘peaky’’ or impulsive the data is. Finally, it is possible to compute SEAT values using rms either from direct measurements of the acceleration at the seat track and seat cushion, or to estimate the seat cushion vibration using transfer functions or transmissibility measurements for the seat/person combination. The last of these has several advantages, in that relating transmissibility to subjective targets provides valuable information on how to engineer a seat to meet such targets. It is then also possible to compute the SEAT value for other types of excitation as long as the input at the seat track is defined, and seat transmissibility measurements are available that were obtained using similar levels of excitation.

This article reports on a study at Stellenbosch University where six subjects were exposed to vibration on seven different seats to study the use of seat transmissibility data and SEAT values to predict the dynamic comfort of automotive seats. In the next section, the experimental procedure to measure the seat transmissibility is discussed and the method used to estimate the SEAT values for a particular road input is presented in Section 3. In Section 4, the procedure used to obtain the subjective data are explained. Section 5 discusses the correlation between the subjective and objective data and Section 6 contains the conclusions and recommendations.

2. Experimental data

The dynamic seat testing facility (DSTF) is a man-rated single axis vibration platform available in the Structures Laboratory of Stellenbosch University. It has a platform that provides for the mounting of test seats with seated subjects. The platform can oscillate vertically for the purpose of testing seat performance under dynamic conditions. The rig comprises a 100 kN servo-hydraulic test actuator with a 125 mm stroke and an operational range of 0–35 Hz. A servo-hydraulic valve is controlled to move the actuator and simulate vertical road vibration on a rigid aluminium platform.

The platform motion is monitored by a displacement transducer that provides feedback to a closed-loop PID controller. The servo-controller facilitates closed-loop force or displacement control. Platform vibrations were restricted to a frequency content of 0.5–20 Hz (the relevant frequency range for whole-body vibration in vehicles). Displacements did not exceed 50 mm about the centred actuator position.

A pair of slotted aluminium extrusion bars is bolted to the platform and provide for the fastening of an aluminium footplate and different seats. An angled wooden footrest (20°) is bolted to the footplate and creates foot support for seated subjects. The seven test seats (Table 3) were fixed to the rig by bolting the seat rails to steel blocks that slide inside the slots of the extrusion bars. This allowed for the accurate positioning of the seats, which is important due to the variation in subject length and seat configuration. The backrests of all the seats were positioned at 24° of inclination while the subjects were allowed to adjust the seats fore and aft so that their legs and feet were comfortable.

Subjects were seated on the reference seat (Seat A) and instructed to place their heels at the intersection of the footplate and footrest. They were instructed to keep their hands in their laps, lean against the backrest, and look straight ahead in an erect driving posture. The participants were allowed to adjust the fore-aft position of the seat, until seated comfortably. Subject posture was checked against the specification of ISO 7096 [12]. The seat index point (SIP) [13] was determined for each subject in this position. The location of the SIP relative to the intersection of the footrest with the footplate was kept consistent throughout the testing of different seats for each subject to minimise the effect of posture on the experimental data.

The input command signal was generated or specified by the operator. The displacement response (measured by the LVDT) and acceleration measurements on the platform, seat-top and seatback were recorded by the data acquisition system. Acceleration measurements were made on the platform (vertical), seat-top and seatback (in-plane and perpendicular). A DC-capacitive-type accelerometer was used on the platform to enable accurate vibration measurement at low frequencies. The use of this sensor resulted in good transmissibility and coherence at low frequencies (below 1 Hz). Seat pad accelerometers were used on the seatback and seat-top as prescribed in ISO 2631 [9]. They are tri-axial piezoelectric sensors with accurate acceleration measurement capabilities above 0.5 Hz. A seat pad accelerometer was taped to the seat cushion with its centre 128 mm from the back of the intersection with the backrest to measure the seat-top vibration. A similar device was taped on the backrest at a distance of 320 mm from the seat cushion [10].

A photograph of the test set-up is shown in Fig. 1.

Six subjects, three males and three females, participated in the study. They were selected to represent the average population in weight and height according to the criteria as shown in Table 1. The selection criteria were similar to the previous work by Van Niekerk et al. [10].

To obtain reliable transmissibility functions the base of the seat was excited in a purely vertical direction, using a vibration input with a flat input spectrum in the acceleration domain, over a bandwidth of 0.5–20 Hz at a rms acceleration level of 1.5 m/s^2. The seat transmissibility was estimated by averaging 50 blocks (block length 1024 points) of acceleration data at the seat track and on the seat, sampled at 128 Hz. The averaged transmissibility for each seat was obtained by computing the average at each frequency line over the six subjects. In all experiments, a close watch was kept on the coherence to ensure that accurate transmissibility estimates were obtained.

Fig. 1. The dynamic seat testing facility at Stellenbosch University.

Table 1
Characteristics of human subjects

Gender and weight percentile	Weight w/o clothes (kg)	Height w/o shoes (m)	Subject number(s)
1 × 5% female	<53	1.47–1.56	1
2 × 50% females	59–66	1.57–1.67	2 and 3
2 × 50% males	70–90	1.68–1.78	4 and 5
1 × 95% male	>90	1.79–1.88	6

The averaged transmissibility data for all seven seats for the following three cases are presented in Figs. 2–4:

- Vertical input at the seat base to vertical output at the seat cushion (Fig. 2).
- Vertical input at the seat base to vertical output on the seatbackrest (Fig. 3).
- Vertical input at the seat base to longitudinal output at the backrest (Fig. 4).

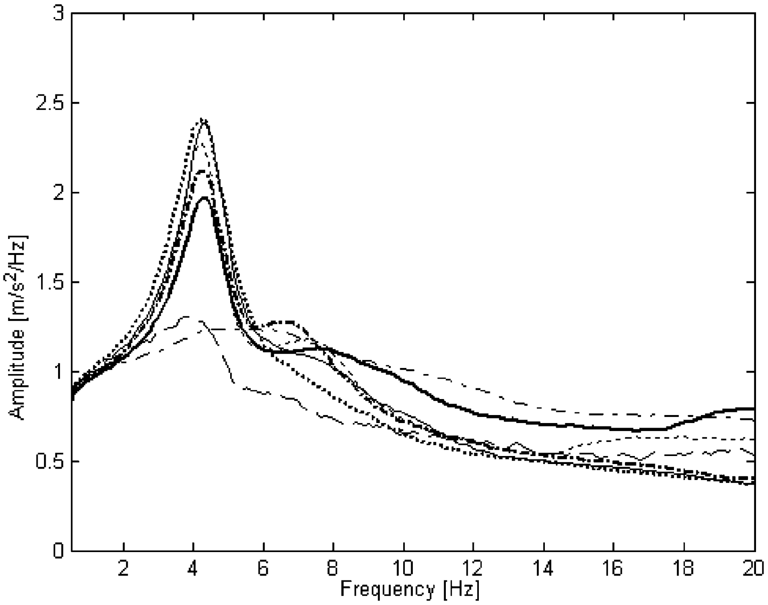

Fig. 2. Averaged transmissibility of all 7 seats for a vertical output at the seat-top due to a vertical input at the seat base.

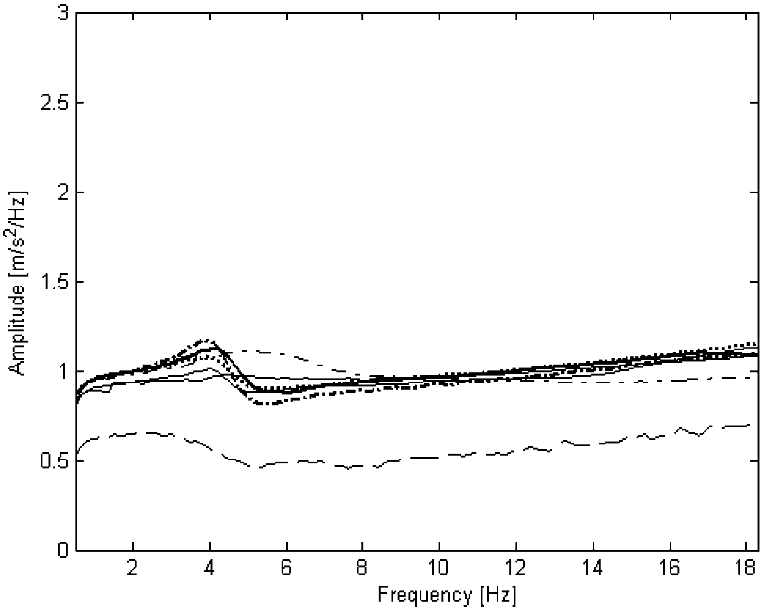

Fig. 3. Averaged transmissibility of all 7 seats for a vertical output at the seatback due to a vertical input at the seat base.

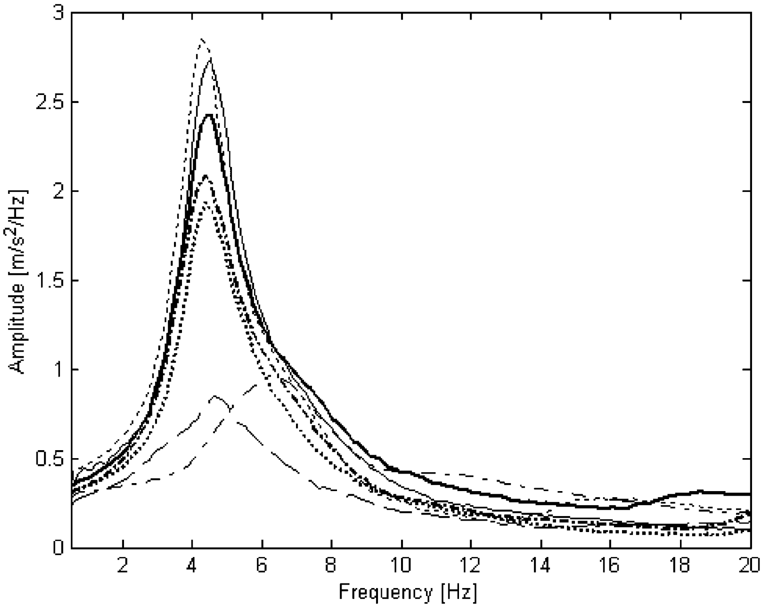

Fig. 4. Averaged transmissibility of all 7 seats for the longitudinal output at the seatback due to a vertical input at the seat base.

3. Estimation of seat values from transmissibility data

It is possible to measure or estimate SEAT values in a number of different ways. For the purpose of this work, where data with low crest factors are being analysed it is sufficient to use the weighted rms values to calculate the SEAT values. This procedure can be completed in the frequency domain using the power spectral densities of the measured vibration and the relevant frequency weighting curves. The following equation describes this method:

$$\mathrm{SEAT\%} = \left[\frac{\int G_{\mathrm{ss}}(f)W_i^2(f)\,\mathrm{d}f}{\int G_{\mathrm{ff}}(f)W_i^2(f)\,\mathrm{d}f}\right]^{1/2} \times 100, \tag{2}$$

where $G_{\mathrm{ss}}(f)$ is the seat vibration power spectral density, $G_{\mathrm{ff}}(f)$ the floor vibration power spectral density, and $W_i(f)$ the relevant frequency weightings for the human response to the vibration in the position and direction that is of interest. The relevant frequency weighting curves are listed in Table 2.

For this study, the weighting curves as defined in the standard ISO 2631 were used. If it is possible to reliably estimate the seat transmissibility, and the system is not highly nonlinear then the power spectral density on the seat can be estimated as

$$G_{\mathrm{ss}}(f) = G_{\mathrm{ff}}(f)|H_{\mathrm{fs}}(f)|^2, \tag{3}$$

where $|H_{\mathrm{fs}}(f)|$ is the seat transmissibility of the vibration from the floor to the seat. It is then possible to calculate the SEAT value as follows:

$$\mathrm{SEAT\%} = \left[\frac{\int G_{\mathrm{ff}}(f)|H_{\mathrm{fs}}(f)|^2 W_i^2(f)\,\mathrm{d}f}{\int G_{\mathrm{ff}}(f)W_i^2(f)\,\mathrm{d}f}\right]^{1/2} \times 100. \tag{4}$$

The vibration input stimulus used for the subjective assessment of the seats was an actual road data recording, measured at three locations on the seat track of a lightweight, economy sedan while driving on a badly corrugated gravel road at 60 km/h. The road surface is a combination of rocks and sand on a straight,

Table 2
Relevant frequency weighting for comfort according to ISO 2631

Direction	Weighting
Seat-top vertical (z)	W_k
Seatback vertical (z)	$0.4W_d$
Seatback longitudinal (x)	$0.8W_c$

Table 3
Estimated averaged SEAT values and the subjective rating for 16 seats

Seat	Vehicle	Averaged measured SEAT values (%)			Averaged estimated SEAT values (%)			Averaged subjective rating
		Seat-top	Seatback vertical	Seatback longitudinal	Seat-top	Seatback Vertical	Seatback longitudinal	
A	Luxury sedan	79	112	60	78	95	63	12.2
B	Economy sedan	74	108	70	75	97	66	11.6
C	Air-suspension truck	56	107	42	42	92	44	7.4
D	Rigid wood with foam cushion	90	112	48	91	106	48	13.8
E	Small pick-up	88	111	65	87	102	65	12.5
F	Economy sedan	73	112	53	76	99	54	11.2
G	Double cab pick-up	69	110	51	71	100	49	10.7

slightly sloping section close to Cape Town, South Africa. A band-pass filter was applied to the road data recording, eliminating all vibrations outside the 0.5–20 Hz range. The filtered vibration was scaled to an rms value of $1.5\,\text{m/s}^2$. The floor-pan vibration contained rigid-body modes (1–2 Hz) and seat-occupant modes (5–9 Hz). Wheel-hop modes are in the frequency range of 10–15 Hz, which is suspected to coincide with the frequency of the road corrugation in this case. The filtered floor-pan acceleration was padded with zeros to create an 8 s vibration signal (2 s of zeros, 5 s of road data and 1 s of zeros) to comprise a single 1024 point data block. The final excitation was reconstructed within 10% accuracy on the DSTF platform when the error was monitored in both the time and frequency domains.

Averaged SEAT values for the seven seats were calculated *directly* by making use of the filtered time domain data, and then averaging across all six subjects for each seat. This method was compared to an *indirect method*, where SEAT values are calculated with the averaged transmissibility from earlier measurements, over all six subjects, and the power spectral density of the input as shown in Eq. (4). In this study, the two methods were compared with the existing data. The relevant results are shown in Table 3.

There is a very good correlation between the measured and estimated seat-top SEAT values ($R^2 = 0.93$) as can be seen in Fig. 6. If the suspension seat is not considered then it is clear that the regression line will have a slope of close to one and pass through the origin.

It was noted that the estimated and actual SEAT values were virtually identical on the seat-top for all the seats except Seat C. The significant difference between the actual and estimated SEAT value of Seat C is attributed to the nonlinearity of the air-suspension. This indicates that caution should be applied when estimating SEAT values for seats with significant nonlinearity.

This result implies that accurate SEAT values can be obtained by measuring the applicable seat transfer functions and vehicle floor vibration PSD, without actually measuring the seat vibration. This supports data gathered by Paddan [14] where a correlation of 0.98 was found between actual and estimated SEAT values on the seat-top. Pielemeier et al. [15] reported a correlation of $R^2 = 0.84$, and Van Niekerk et al. [10] $R^2 = 0.94$ between averaged measured SEAT values and estimates from averaged transmissibility.

4. Subjective data

Reliable subjective dynamic seat comfort assessment was achieved using the virtual seat method [10]. It is a paired comparison test in which each trial consists of two stimuli: a virtual reference stimulus, which is the same for all subjects on all seats, and an alternative stimulus, which is a scaled input at the base of the seat. The reference and alternative vibrations are evaluated against each other in back-to-back comparisons and evaluated through their relationships with the reference.

The platform is used to generate a reference vibration that is the **same on the seat cushion** for every subject on every seat. This is achieved by an iteration procedure known as service load reconstruction. The input of the platform at the base of the seat is adjusted until the vibration measured at the seat cushion has converged to the desired reference vibration. This vibration input is then used as the reference input vibration for that specific subject for every trial on a particular seat.

Seat test vibration stimuli (referred to in this text as alternative stimuli), are reconstructed identically **at the seat track** for the different seats and subjects, but are scaled in magnitude for different trials, allowing the seat properties to filter the vibration. These alternative stimuli are varied during a set of trials for each subject on a particular seat.

The major advantage of the virtual seat test method are that the time delay between test trails are removed because the reference vibration and alternative stimuli are played back-to-back in a set of trails. At the same time, the reference vibration on the seat cushion is the same for every seat and thereby any static comfort bias is also eliminated.

Each pair of stimuli was followed by a time slot, in which the subject was forced to choose which stimulus was **preferred** in terms of **comfort**. If the reference stimulus was chosen as the most comfortable, a “positive” response was recorded. If the alternative stimulus was chosen as the most comfortable, a “negative” response was noted. Better seats would improve the comfort of all of the scaled alternative stimuli, so that a more severe input (at the seat track) would match with the virtual reference (at the seat cushion). Poorer seats would reduce the comfort of all of the scaled alternative stimuli, so that a milder input (at the seat track) would match with the virtual reference (at the seat cushion).

The subjective rating scale used was a just noticeable difference (JND) scale, which refers to the size of the smallest change in whole body vertical vibration that a typical subject can detect as described by Pielemeier et al. [16] and Mansfield and Griffin [17]. One JND is taken as a 10% increase in the level of vibration.

The road vibration recording (Fig. 5) was scaled larger and smaller with a factor of 1.1 for each step, resulting in a series of vibrations that were 1 JNDs apart. There were 30 scaled, alternative vibrations within the safe vibration exposure and actuator limits. The rms values of the un-weighted, filtered vibrations ranged from $0.24\,\mathrm{m/s^2}$ (Alternative 30) to $3.80\,\mathrm{m/s^2}$ (Alternative 1). Alternative 15 (the middle alternative) had an rms value of $1.00\,\mathrm{m/s^2}$, and the original road data recording was equal to Alternative 11. The reference vibration was recorded by playing Alternative 11 at the seat track and measuring vibration with subject 4 seated on the seat cushion of Seat A (Fig. 6).

Pielemeier et al. [15] suggests that all subjects undergo a training period of 240 trials before their learning curve stabilises. All subjects participated in at least 240 trials of evaluating the most comfortable stimulus in a paired-comparison, forced-choice procedure. The subjects were thus trained prior to participation in subjective ride comfort testing. It is assumed that there was no further improvement in the subjects’ discernment of vibration levels after this period. The trials for the virtual seat method were governed by a 2-track, interleaved, 2-up-1-down Levitt, paired comparison procedure. The choice of this procedure is fully motivated in Appendix A. This procedure typically involved the presentation of about 50–60 pairs, and took about half an hour per seat and subject to converge to the subjective level of equivalence (the 50:50 point). The point on the psychometric function at which the probability of choosing the virtual reference versus the alternative is 50%, is the point at which they match in the subject’s perception, and that JND level is assigned to the seat as the subjective rating. This means that lower JND levels are better because they indicate that the

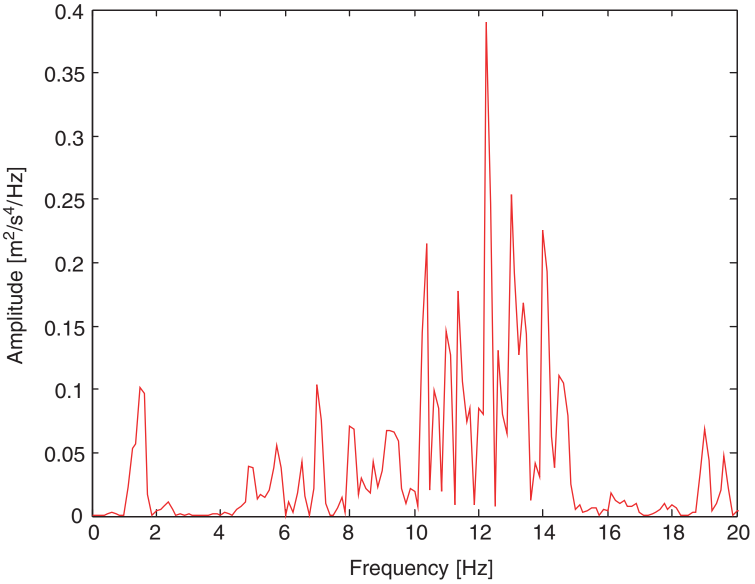

Fig. 5. Power spectral density of the vertical rough road input at the seat track.

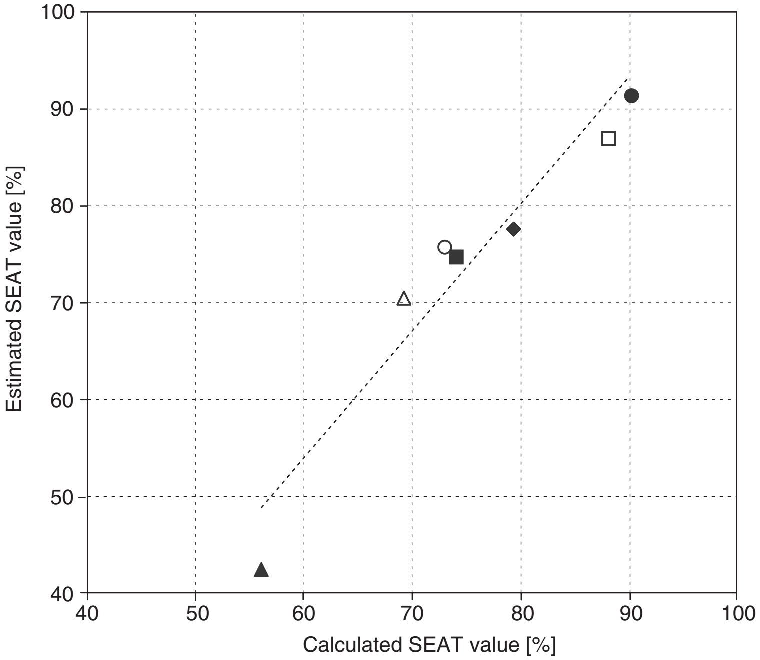

Fig. 6. Correlation between SEAT values from measured time data (*direct method*) and calculated using the averaged transmissibility for the seven seats (*indirect-method*) on the seat-top. (Solid triangle: Suspension seat.)

seat attenuated the vibration of a higher-level input alternative at the seat track enough to match with the reference.

Based on an ANOVA analysis of the data, there is a statistically significant difference between the ratings of the seven seats, but not between the ratings of the subjects. This warrants the averaging of the subjective

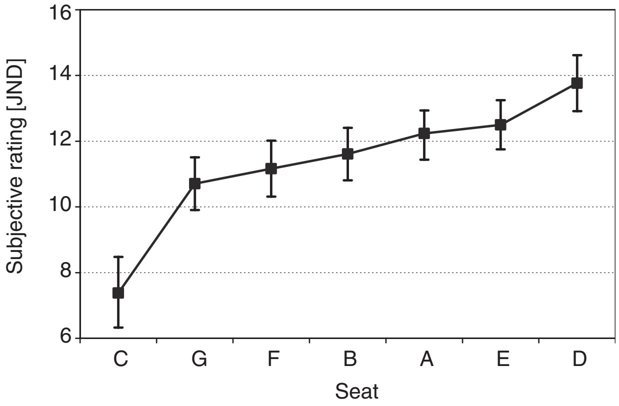

Fig. 7. Mean and 95% confidence levels for subjective ratings.

ratings and confidence intervals over the six subjects, shown as a function of seat in Fig. 7. These results have been sorted from the best to the worst rating. This is the data used for the averaged subjective ratings in subsequent sections. The mean values of the subjective ratings are listed in Table 3.

5. Correlation of subjective and objective data

Trying to correlate *individual* subjective ratings and measured SEAT values in the vertical direction at the seat-top, results in good to poor correlation. The results where each subject's subjective rating is correlated, against the measured individual SEAT values in the vertical direction at the seat-top are shown in Fig. 8. (Note that subjects 4 and 5 were not tested on Seat C due to difficulties in reproducing the reference vibration on the seat due to the nonlinear behaviour of the suspension seat for these two subjects.)

Subjects 1 and 2 seem to be less sensitive to different levels of vibration, or find it more difficult to discriminate between different vibration levels, since the slopes of the curve-fit (both 0.08) are smaller than for the other subjects. This reduction in sensitivity also leads to lower correlation between their subjective ratings and the measured SEAT values. Subject 5, with the highest correlation ($R^2 = 0.93$), also has the steepest slope and hence this subject seems to be much more sensitive to vibration. The complete correlation data is presented in Table 4.

The next step was to investigate the correlation between the averaged, estimated SEAT values and the averaged, subjective ratings obtained in the subjective evaluation study. The estimated SEAT values were used as there was not a significant difference between the measured and the estimated SEAT values as shown in Fig. 6. In Fig. 9, the SEAT values for vertical vibration at the seat-top are compared to the subjective ratings and again good correlation, $R^2 = 0.97$, for the estimated SEAT values, in only the vertical direction, at the seat-top, were obtained.

SEAT values calculated at the seatback in the longitudinal direction and the overall averaged subjective ratings does not correlate well (both $R^2 = 0.46$) as shown in Fig. 10. The general trend that smaller SEAT values in this direction do correspond with an *increase* in dynamic comfort is however noticeable in Fig. 10. This study fails to find the relevance of seatback vibration and SEAT values on dynamic seat comfort as seatback SEAT values do not correlate well with subjective assessments.

Griffin [1] proposes the computation of the geometric mean as a way to combine multiaxis vibration. If this approach is extended to combining SEAT values from a single input at the seat track, as is the case [12], then

$$\mathrm{Comb}_1 = \sqrt{\mathrm{TopZ}^2 + \mathrm{BackX}^2 + \mathrm{BackZ}^2}. \tag{5}$$

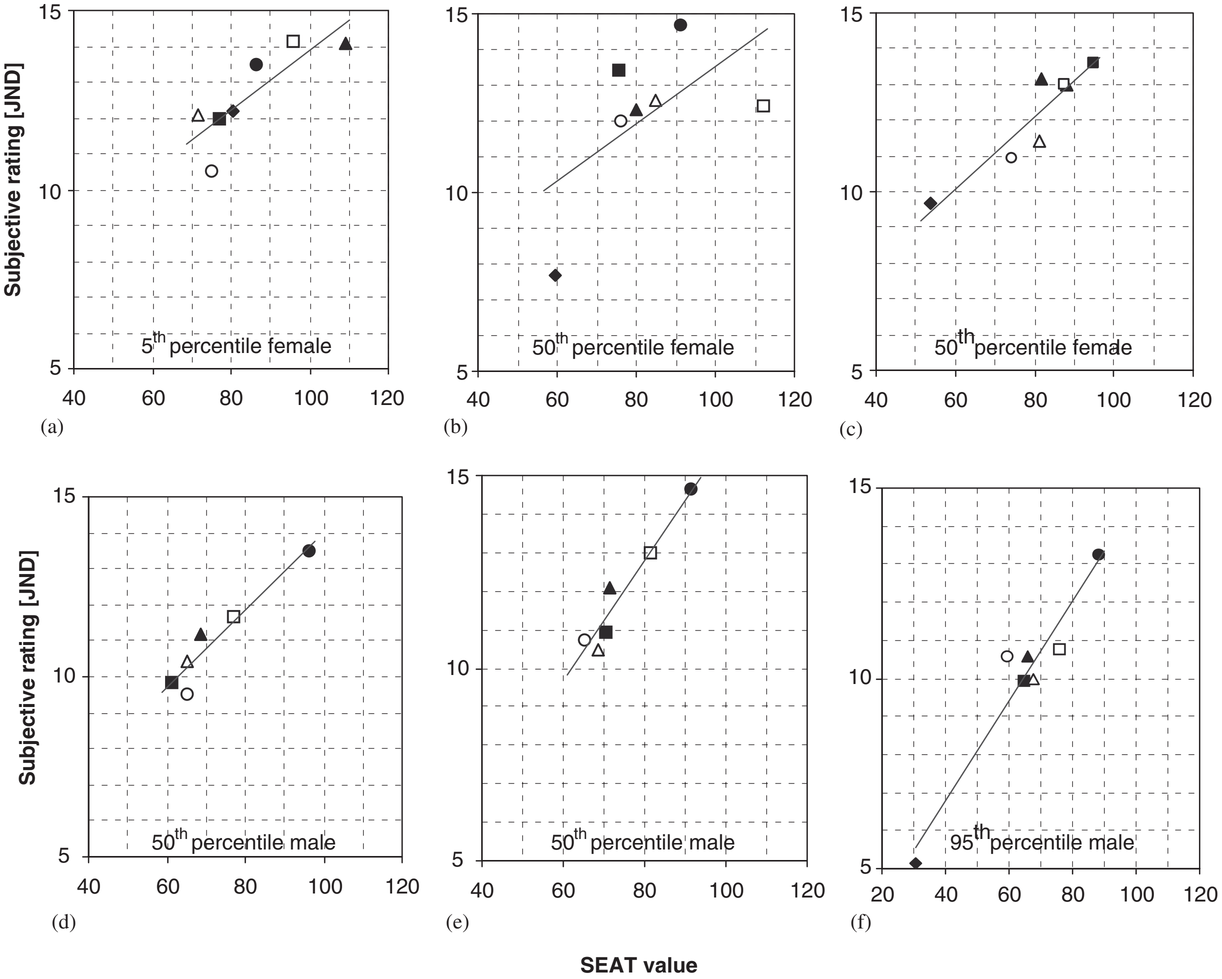

Fig. 8. Correlation between individual measured SEAT values (vertical track input to vertical output at the seat-top) and the individual subjective ratings.

Table 4
Correlation between individual subjective ratings and measured SEAT values

Subject #	R^2	Slope
1	0.69	0.08
2	0.37	0.08
3	0.85	0.10
4	0.92	0.11
5	0.93	0.16
6	0.92	0.13

Combined multiaxis SEAT values also fail to correlate well with subjective dynamic seat comfort ratings ($R^2 = 0.00$). A possible reason for this lack of correlation is that the SEAT values for the vertical seatback vibration only vary with about 5% between seats.

If only the vertical seat-top and longitudinal seatback values are combined as shown in

$$\mathrm{Comb}_2 = \sqrt{\mathrm{TopZ}^2 + \mathrm{BackX}^2} \tag{6}$$

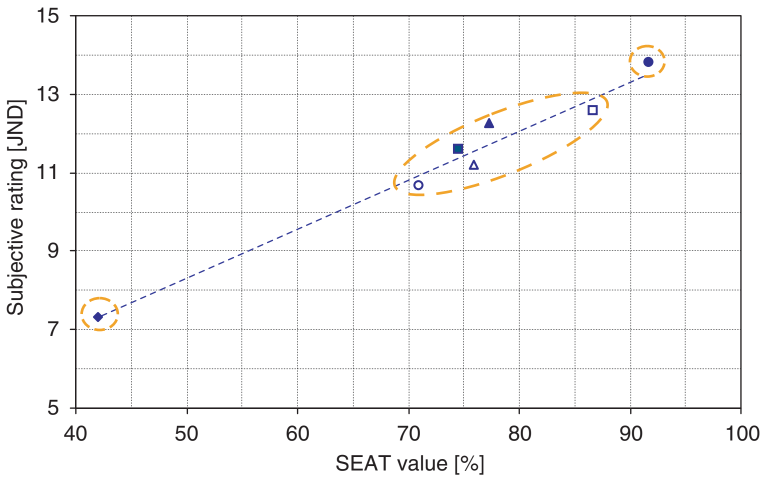

Fig. 9. Correlation between estimated SEAT values (vertical track input to vertical output at the seat-top) and the subjective ratings.

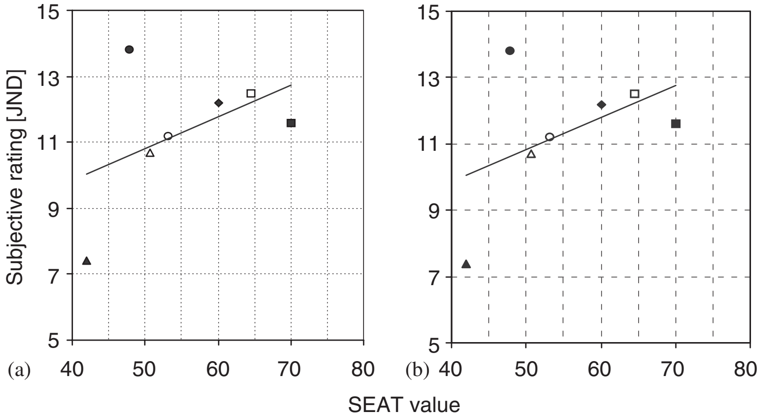

Fig. 10. Correlation between measured SEAT values (vertical track input to vertical and longitudinal output at the seatback) and the subjective ratings.

then there is a good correlation between subjective ratings and the combination of vertical SEAT values in the seat-top and perpendicular seatback ($R^2 = 0.88$). Van Niekerk et al. [10] reported correlations of $R^2 = 0.78$ in both the aforementioned cases. However, it seems that the contribution from the seatback in the vertical direction did indeed have a small effect in improving the correlation. This may also have something to do with the way in which the subjects decided to evaluate the vibration by concentrating their attention on the vertical component at the seat-top, as it was the most prominent.

The results of the correlation for these four different combinations are listed in Table 5.

From the table it seems that the best one can do is to only consider the vertical seat-top response when attempting to correlate objective measurements to subjective ratings.

Future work includes further investigation into the relevance of seatback vibration on dynamic seat comfort and the mechanics of vibration transmission to the seatback. If seatback vibration contributes significantly to dynamic seat comfort a metric that correlates objective measurements with subjective dynamic seatback comfort perception remains to be identified or developed.

Table 5
Correlation of SEAT value combination

Combination	Description	R^2
Seat-top vertical	TopZ only	0.97
Seatback longitudinal	BackX only	0.23
Comb_1	Geometric mean of TopZ, BackX and BackZ	0.00
Comb_2	Geometric mean of TopZ and BackX	0.88

6. Discussion and conclusions

In this study, it has been shown that the virtual seat test method results in conclusive subjective dynamic seat comfort assessments. Paired comparison techniques eliminate subject and static seat comfort bias from the dynamic seat comfort assessment. A 2-up-1-down, two-track interleaved, Levitt-procedure is more efficient and accurate than the psychometric function method of constants, used by Van Niekerk et al. [10] to assess dynamic seat comfort. The greater efficiency of the 2-up-1-down, two-track interleaved, Levitt procedure is attributed to its adaptive nature, which results in the gathering of less unnecessary data. Procedure reliability was improved by averaging two independent tracks that confirm the level of convergence. The interleaved fashion of the tracks eliminates subject bias as it disguises the converging pattern of the Levitt procedure.

The reference stimulus used for dynamic seat comfort assessment in this study was a road vibration recording with an rms value of $1.5\,\text{m/s}^2$ at the seat track. The PSD of the input signal shows that the input vibration has most of its energy between 10 and 15 Hz (wheel-hop modes and road corrugation), but also some vibration between 4 and 10 Hz (containing seat-occupant modes) and at 2 Hz (rigid body modes). The reference stimulus used by Van Niekerk et al. [10] was a rough road vibration with most of its energy concentrated between 12 and 16 Hz and an rms value of $1.6\,\text{m/s}^2$ at the seat track with all the rigid body modes filtered out. Subjective dynamic seat comfort has now been correlated with estimated SEAT values on the seat-top for two different road vibrations with different spectral contents.

The correlation between the measured and estimated SEAT values, from seat transmissibility measurements, is very high on the seat-top ($R^2 = 0.93$). This gives one confidence to use only reliably measured transmissibility functions to estimate SEAT values for a variety of applications.

The six subjects who participated in this study were carefully selected to comprise a profile that represents the general population. The results show a significant improvement in the correlation between measured and estimated SEAT values and subjective-objective dynamic seat comfort, when individual values are averaged over the test subjects. Van Niekerk et al. [10] reported a similar improvement in the correlation of averaged results for six subjects selected according to the same criterion. The correlation in this study was found to be $R^2 = 0.97$ compared to 0.94 in Ref. [10], albeit for only seven seats versus the 16 seats in the previous study. Including the seatback vibration did not improve the correlation.

The conclusions of this study suggest that the SEAT values, estimated from averaged seat-top transmissibility of six carefully selected subjects, can be used to select the best seat for a specific road vibration input.

Acknowledgements

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Appendix A

Van Niekerk et al. [10] used the psychometric method (Fig. A1) of constants as a paired comparison scheme in the virtual seat method to find the subjective ratings. This scheme converges to the alternative stimulus,

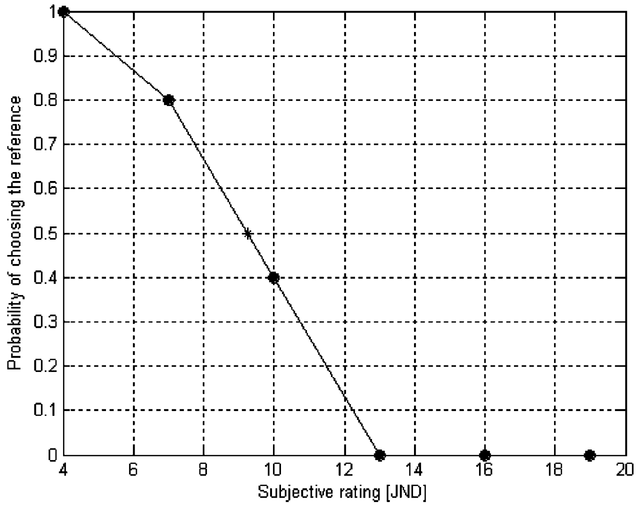

Fig. A1. The psychometric method of constants. (Solid circle: Probability of choosing the reference vibration at tested intervals, Star: Derived point of equivalence, $X_{50} = 9.25$.)

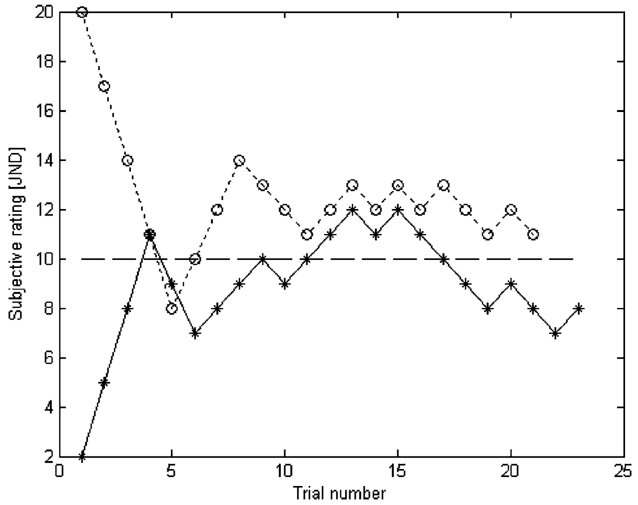

Fig. A2. Two-track, interleaved, 1-up-1-down Levitt procedure. (Open circle dot line: Track A, Star solid line: Track B.)

which is perceived to be equal in comfort to the reference stimulus. Van Niekerk et al. [10] reported that the psychometric method of constants needed, on average, 100 trials to converge to the subjective level of equivalence.

The method of constants proves to be inefficient if one is interested in estimating only one point on the psychometric curve (as is the case here, where only the point of subjective equality is to be determined). This inefficiency is caused by the fact that a large number of observations are placed at some distance from the point of interest. The data is pooled at the predetermined stimulus levels, and then a curve is fitted through the pooled data. This approach also does not allow for gradual changes in parameter values during the course of the test [18].

In this study, the performances of three paired comparison schemes were compared for nine subjects on the reference seat. The psychometric method of constants, used by Van Niekerk et al. [10], was compared with a two-track interleaved, 1-up-1-down Levitt procedure [19] (Fig. A2) and the 2-up-1-down, two-track interleaved Levitt procedure [20] (Fig. A3).

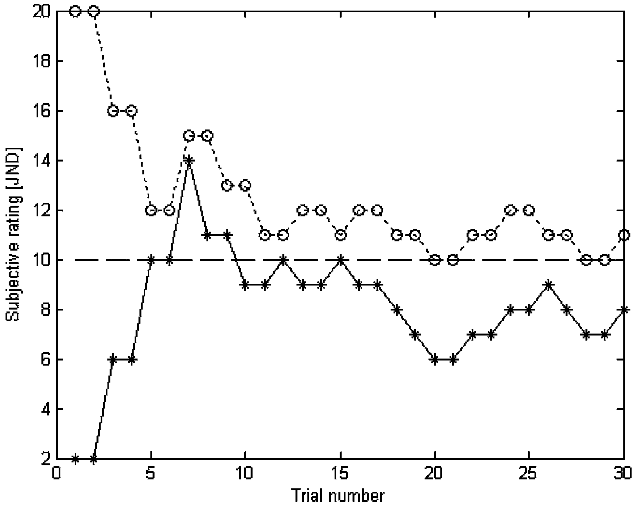

Fig. A3. Two-track, interleaved, 2-up-1-down Levitt procedure. (Open circle dot line: Track A, Star solid line: Track B.)

Parameters such as the number of trials, accuracy, variance of the subjective level of equivalence, and the number of trials with pairs close to (within 1 JND) or equal to each other were used to decide on the best subjective dynamic seat comfort assessment procedure.

Levitt procedures are adaptive procedures in which the stimulus levels of the current trial are determined by the subject's response in the previous trial [18]. They promised to be more economical and more efficient in the placement of observation points as most observations are placed near the point of subjective equality. This procedure converges more rapidly than the method of constants with the possibility of greater accuracy since the step size can be changed as the algorithm converges. The bias due to the predictability in the response of a single track can be reduced by interleaving two independent tracks [19].

Both the Levitt procedures that were tested had two independent interleaved tracks that used the same *reference signal* for their paired comparison trials. One of the tracks, which we refer to as the "A sequence", is started at a level well above the *reference*, so that the *reference signal* will be chosen as more comfortable at the start. The "A sequence" is interleaved with an opposing "B sequence", which starts at a distinctly lower level than the *reference*. The initial step sizes of the tested procedures are stated in Table 1. The step size was reduced by 1 JND after each reversal.

A 1-up-1-down, two-track interleaved Levitt procedure is economic as it only takes one trial to order a reversal. The most important difference between the 1-up-1-down and 2-up-1-down procedures is that the 2-up-1-down procedure estimates two points on the psychometric curve (79% and 21%), whereas both tracks of the 1-up-1-down procedure estimate the subjective point of equivalence (50%). Standard, interleaved Levitt procedures have been used with success in subjective equivalence testing [15,19], but not yet for the testing of dynamic seat comfort.

Table A1 shows a summary of the subjective procedure test results. The 2-up-1-down, two-track interleaved, Levitt procedure with an initial step size of 8 JNDs was chosen as the subjective seat comfort assessment procedure. Of the methods tested, this method was the second-most economic and most accurate in predicting the subjective level of equivalence, with the smallest variance and the least trials close to the *reference stimulus* level. Ten reversals or a maximum of 50 trials will be required for a test track to converge. The average of the last six reversals will be taken to determine the relevant points on the psychometric curve.

Only a limited amount of procedures and procedure parameters were tested. The evaluation of these subjective dynamic seat comfort assessment procedures were by no means conclusive, but merely suffice to prove that the procedure implemented in this study was accurate and effective in the determination of the subjective point of equivalence.

Table A1
Subjective procedure test results

Criteria	Psychometric function method of constants	2-Track, interleaved, Levitt procedures			
		1-Up-1-down Initial step 3 JNDs	2-Up-1-down Initial step 4 JNDs	2-Up-1-down Initial step 6 JNDs	2-Up-1-down Initial step 8 JNDs
No. of trials	91	45	59	55	53
Error (%)	0.8	0.6	4.4	2.9	0.2
Variance (%)	7.1	8.2	6.4	7.4	6.1
Trials equal	30	9	9	9	9
Trials close	30	25	25	25	24

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