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Tolerance Specification and Relevance of Key Parameters on Customer Satisfaction for Automotive Touch Controls with Active Haptics

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***Abstract*—Modern cars often have touch-based controls with active haptics. In the design of touch controls with active haptics, the tolerances of several parameters that influence user experience and production costs need to be defined. To identify the tolerance specification and relevance of key parameters, a subject study with 20 participants was conducted using a highly precise active haptics simulator. The results show that haptic feedback and feedback reliability are crucial for customer satisfaction, as missing signals are immediately perceived and cause significant dissatisfaction. Force threshold and feedback latency are noticeable and lead to dissatisfaction once certain values are exceeded. The deterioration of the feedback waveform and acoustics is noticeable and shows a tendency to dissatisfaction but is not exclusively rated negatively by all participants. The study emphasizes the importance of harmonizing these parameters with the specifications of active haptic controls to prevent over- or under-specification, ensuring an optimal user experience.**

***Keywords*—** *automotive user interface, control element, active haptic feedback, vibrotactile feedback, force threshold, feedback latency, feedback waveform, feedback acoustics*

I. Introduction

The design of touch controls with active haptic feedback in automotive human-machine interfaces (HMI) presents a complex challenge: balancing production costs and technical performance while maximize user experience. Identifying the key parameters that influence user experience is crucial to avoid over-specification, which unnecessarily increases production costs, and under-specification, which negatively affects product quality and usability [1]. Knowledge of the key parameters and optimal tuning are essential for cost efficiency and user-friendly design.

Modern automotive interior design strategies with surfaces that are as integrated and seamless as possible often demand touch-sensitive control elements. Cost is another crucial factor that favors touch controls under certain conditions. To provide haptic feedback on touch controls a passive touch plate (PTP) can be added. With this technology, several functions are arranged on a closed touch-sensitive surface that is movably mounted on a micro-switch. In this context, the concept is referred to as passive haptics, where the user introduces the energy required for feedback into the system during actuation. Alternatively, haptic feedback on touch controls can be implemented using active haptics. In this case, the feedback is generated independently of the user's energy input, typically through electromechanical actuators. Active haptics offer various advantages over a PTP, such as haptic feedback in slide use cases, and are therefore preferred in certain applications [2]. Automotive touch controls with active haptics typically incorporate capacitive sensing to detect finger position on the control surface and force sensing to measure actuation force. For both function activation and haptic feedback, the system must detect the finger's position and ensure that a defined actuation force is applied to prevent accidental activation. Since drivers must focus on their primary task of driving, they often glance briefly at the control element and rely on tactile exploration to locate the button surface [3]. With only touch sensing unintended activations are the result. To prevent this, a defined actuation force threshold is crucial before activation [4]. In contrast, force sensing is typically not required in consumer electronics, where users can entirely focus on operation [5, 6]. The actuation force threshold for push feedback is typically around 4.5 N, while the release feedback threshold, with a hysteresis of approximately 1 N, is around 3.5 N. These values are generally within this range but can be adjusted to create different characteristics for specific functions or installation positions or even dynamically adapted to driving conditions.

The parameters and effects on subjective perception for passive haptics have been extensively studied for translational [7] and rotary controls [8], with a comprehensive summary provided by Bubb [3]. While in passive haptics of translational controls, the snap primarily determines subjective perception [9], active vibrotactile feedback waveform involves a multitude of decisive parameters [10–12]. The primary focus of most studies is on the feedback waveform [1, 13, 14]. But also other factors, such as the force thresholds discussed above determine the user experience. As the literature mostly lacks reports on the critical parameters of active haptic controls, prior to this study an expert team of experienced control designers identified force threshold accuracy, feedback latency, feedback reliability, feedback waveform, and feedback acoustics as the key technical parameters that influence the user experience.

Feedback latency is defined as the time between exceeding the force threshold and generating haptic feedback. This latency depends not only on the actuators used but also on the control element's processing frequency. In specific applications, the logic for triggering haptic feedback is linked to the actual function execution. As a result, signal transmission times to a central vehicle control unit via an automotive BUS system can significantly impact feedback latency [15]. Haptic feedback latency significantly influences user satisfaction, even when task performance remains unaffected [16–18]. Therefore, latency should be considered a critical design parameter in haptic interface development [15–20].

Feedback reliability and missed feedback events represent another critical challenge in haptic system design. Complex evaluation algorithms process force and touch sensor data to detect activations. Failures in this process, whether due to sensor inaccuracies or system issues, can result in missing haptic push or release feedback. Beyond system reliability, manufacturing tolerances can lead to deviations in waveform and acoustics, which influence the perceived quality of haptic feedback. Fluctuations in actuator performance, suspension characteristics, and manufacturing defects can result in unintended variations.

This study focuses on the subjective effects of force thresholds, feedback latency, missed feedback events, and feedback waveform & acoustic variations in active haptic touch controls on user perception. To conduct this research and display the various stimuli in a high range, while guaranteeing precise and highly reproducible stimuli the Active Haptic Simulator was developed. Based on these parameters, systematic stimulus sets were designed, and participants were asked to report perceived differences and evaluate the stimulus sets using a semantic differential.

II. Method

A. Participants

A total of 20 participants (7 female and 13 male) were recruited for this study who volunteeted to participate. The age group distribution is as follows: age 21 – 30 n = 8, age 31 – 40 n = 5, age 41 – 50 n = 4, and age 51 – 60 n = 3. All participants work in the automotive sector, none had prior experience with the assessment or evaluation of haptic feedback. All participants were right-handed.

B. Apparatus: Active Haptics Simulator

The Active Haptics Simulator has a modular design. At its base is a solid steel plate with a three-dimensional force sensor, which is the basis for the passive and active modules mounted on it. The passive module generates an adjustable actuation travel and a customizable force characteristic that enables the simulation of a wide range of mechanical behaviors. A progressively increasing force-displacement curve with 0.6 mm actuation travel at 4.5 N actuation force was used for all tests. The active module utilizes one piezoelectric actuator per axis and a metal leaf spring suspension to provide diverse and precise three-dimensional vibrotactile feedback. A smooth aluminum surface was used for all tests. A National Instruments CompactRIO real-time controller and specially developed LabVIEW software were used for control and data recording. The measured latency is < 1 ms, and the practical measurement accuracy of the force sensing is ± 0.01 N. In all trials, the direction of the vibrotactile haptic feedback was in line with the proximal-distal axis of the participants' index finger and parallel to the longitudinal axis of the vehicle. The vibrotactile feedback was kept constant across all trials, except in the section on Variation of the Feedback Waveform, where it was systematically altered. A 0.5-period sine wave at 100 Hz served as the standard stimulus.

C. Stimuli

All stimuli were determined by a team of experts consisting of three developers with extensive experience in haptics. In addition to objective quantifications, this approach ensured that all differences were clearly perceptible and realistically achievable within the scope of possible designs and quality variations.

1) Variation of the Actuation Force Treshold: The stimuli used to investigate the variation in the force threshold were designed to reflect the tolerance of the force sensor used in a control element. A procedure with a total of six stimuli sets, each comprising ten activations, was chosen. The reference stimulus set maintained constant values of 4.5 N for the push feedback and 3.5 N for the release feedback. The five additional stimuli sets, K1 to K5, were defined with varying tolerances: K1 with ± 0.1 N, K2 with ± 0.5 N, K3 with ± 1.0 N, K4 with ± 1.5 N, and K5 with ± 2.0 N. The values for the push force threshold of the six sets, each with ten activations, are shown in Fig. 1, while the values for the release force threshold are analogous, consistently with a 1 N hysteresis below the push threshold.

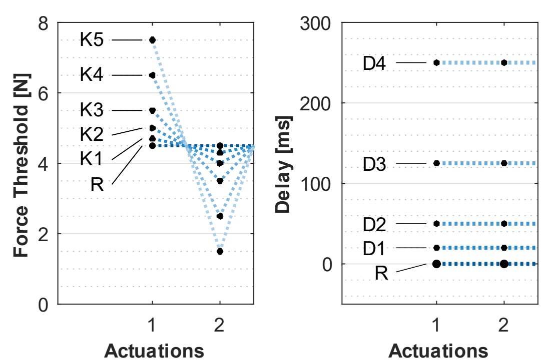

Fig. 1. Stimuli sets (Reference and K1–K5) for the force threshold parameter (left), and stimuli sets (Reference and D1–D4) for the feedback latency parameter (right). Only the first two of ten actuations are shown. For the force threshold parameter, the alternating ± force levels continue throughout all ten actuations within a stimuli set, whereas for the feedback latency parameter, the latency remains constant within each set.

2) Variation of the Feedback Latency: Four stimuli sets with constant latency within each stimulus set were created to investigate the influence of feedback latency. The reference set had no systemically applied latency for push and release feedback. The four additional sets shown in Fig. 1, D1 to D4, were defined with varying latency times: D1 with 20 ms, D2 with 50 ms, D3 with 125 ms, and D4 with 200 ms.

3) Feedback Reliability: Four stimulus sets were designed to investigate the impact of missed feedback from control elements. The reference set involved no missed feedback, while stimulus set M1 included the sporadic absence of release feedback, M2 had a sporadic absence of push feedback, and M3 featured a sporadic absence of both push and release feedback. In all sets with missing feedback, feedback failures occurred for four activations. To ensure comparability, the sequence of activations was synthetically pre-determined and identical across all sets, as illustrated in Fig. 2. This sequence was established with an expert panel and reflects realistic malfunction patterns observed in faulty control elements.

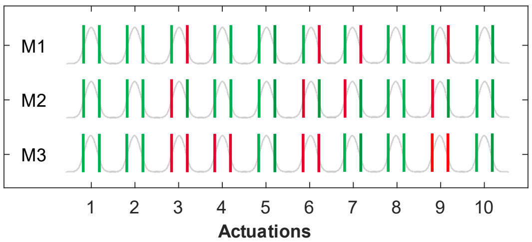

Fig. 2. Stimuli sets M1 - M3 for the missed feedback parameter. The gray line illustrates an example of the force-time curve over the 10 actuations, with vertical lines for the push and release feedback. Delivered feedback signals are shown with a green line, and missing feedback in red.

4) Variation of the Feedback Waveform: An expert team selected two stimuli with medium and long signal lengths to determine the effects of varying the feedback waveform. These stimuli could be clearly distinguished from each other and serve as exemplary representations of feedback waveform variations resulting from different technologies or production fluctuations. The haptic feedback was measured without load using a 3D acceleration sensor (PCB356A03) attached to the surface. The duration of the haptic stimulus was determined based on the first and last measured vibration values that exceeded an amplitude of 10 m/s². The reference stimulus had a duration of 5 ms, while the medium and long stimuli measured 25 ms and 50 ms, respectively.

5) Variation of the Feedback Acoustics: To investigate the impact of variations in feedback acoustics, two additional stimuli were evaluated alongside the reference stimulus, which produced a barely audible sound. These additional stimuli were each overlaid with a 800 Hz and 2000 Hz high-frequency oscillation, resulting in a slightly tinny and tinny sound.

D. Procedure

The study was conducted in a quiet, controlled environment within an automotive seating box, as depicted in Fig. 3. Prior to the experiment, all participants provided informed written consent for participation and data collection, in accordance with ethical guidelines and general data protection regulation. The participants were instructed to find a comfortable position in the driver's seat. The experimenter then collected personal information, including gender, age group, and experience level, and briefed the participants on the procedure. The participants were instructed to operate the control surface of the active haptics simulator, located in the center console, using their right index finger. They were asked to envision the control surface as a touchpad for interacting with the vehicle's central HMI. To simulate a driving posture, a screen in front of the participants displaying the questionnaire effectively diverted their gaze, preventing visual focus on hand movements. Additionally, they were instructed to completely lift their index finger off the control surface between each interaction. This procedure was designed to reflect typical in-vehicle use, where both hands are primarily on the steering wheel, and continuous contact with the user interface is uncommon. There was no functional or visual feedback about the operation. As haptics of control elements are difficult to assess for untrained participants, minimizing distractions is essential to ensure high accuracy and data quality.

The study was structured by the five different parameters to be tested. The order in which the parameters were tested was randomized between subjects to avoid order effects. Participants were not informed of which specific parameter was being altered during the experiment. At the beginning of each parameter, the reference stimulus was presented for evaluation. Subsequently, the subjects were presented with the stimuli sets of the respective parameter in ascending intensity of the variation range. For each stimulus set, the participants were asked whether they detected a difference compared to the previous stimulus set (yes/no). If a difference was found, the participants were asked to rate the perceived change on the questionnaire. If there was no difference found, the result of the previous respectively the reference stimulus was used. In this way, it is avoided that a few very sensitive test subjects can strongly influence the evaluation result.

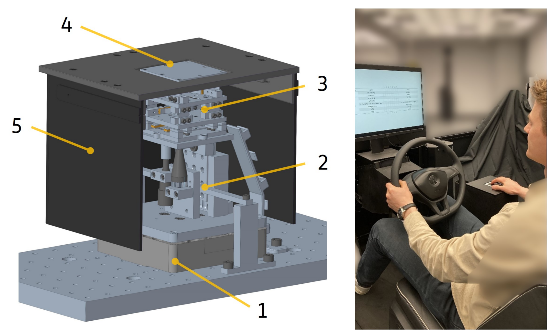

Fig. 3. Active Haptics Simulator (left) consisting of the base and force sensor (1), passive module (2), active module (3), touch surface (4), and housing (5). Evaluation setup (right) with the Active Haptics Simulator integrated into the center console, tested in an automotive seating box.

The questionnaire consists of four bipolar adjective pairs (good/bad, does not meet expectations/meets expectations, unpleasant/pleasant, cheap/high quality). The negatively connotated adjectives were located on the left side of the questionnaire, and the positive adjectives were on the right side. A 7-point Likert scale was used for rating, which was arranged in ascending order from left to right. The mean of the four adjective ratings was used to evaluate the rating results. A low rating is, therefore, generally to be understood as negative and operationalized as dissatisfaction, and a high rating as positive. The participants communicated the results verbally to the experimenter. As a guideline for their orientation, participants were able to see their evaluations of the reference stimulus set throughout the procedure. Hence they were able to adjust their assessments for the current stimulus set based on their previous ratings. The entire procedure lasted approximately 25 minutes.

III. Results

The following result figures consist of two diagrams: The upper diagram contains the percentage of participants stating a difference compared to the previous stimuli set. This can be interpreted as a psychometric function and therefore a Weibull function was applied, although the statistical basis is limited due to the study design (one trial per participant). However, it was not the goal of this study to develop a full psychometric function. For technical application, the combination of detection probability and customer satisfaction is of primary interest. The lower diagram shows the mean rating of the four bipolar adjective pairs of the semantic differential for the stimuli sets tested. The additional visualization of the ratings separated by each of the four bipolar adjective pairs did not provide further insights and was therefore not included in the paper. For the rationally scaled parameters actuation force threshold and feedback latency the mean values are connected with an interpolated dotted line as a guide for the eye.

Before statistical analysis, normal distribution was confirmed using the Shapiro-Wilk test. Statistical analysis was performed using a one-way analysis of variance (ANOVA) followed by the Tukey-HSD test.

A. Variation of the Actuation Force Treshold

Fig. 4 shows the results for the stated difference and the mean rating on the semantic differential for the parameter Force Threshold. The reported differences for the stimuli K1 (± 0.2 N) and K2 (± 0.5 N) are 30 % and 35 % respectively. Only the stimuli K3 (± 1.0 N), K4 (± 2.0 N), and K5 (± 3.0 N) are detected by 65 %, 75 %, and 85 % of the subjects. As in the determination of the perception threshold with a psychometric function, the 50 % stated difference point is reached between ± 0.5 N and ± 1.0 N. Based on the interpolation of the mean ratings, this value is determined to be ± 0.7 N.

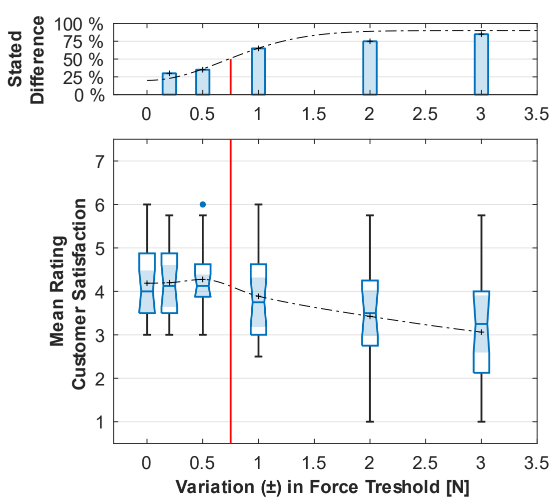

Fig. 4. Stated difference and mean rating of the customer satisfaction for the parameter actuation force treshold. The red line highlights the interpolated position of the 50 % stated difference at ± 0.7 N. The parameters of the Weibull function according to [21] were defined as follows: $\gamma = 20$ % and $\lambda = 10$ % were assumed based on the study design, while $\alpha = 0.98$ N and $\beta = 2$ were fitted to the data.

Below this value, the rating is approximately constant at the level of the reference stimulus set without variation in the force threshold. The reference stimulus (M = 4.2, SD = 0.88) is rated very centrally on the scale. As the variations in the force threshold become larger and more noticeable, the ratings continuously are becoming more negative. The highest tested variation in force threshold with stimulus set K5 is also rated the most negatively (M = 3.1, SD = 1.37). However, due to the high dispersion, the results do not show statistically significant differences.

B. Variation of the Feedback Latency

The results for the parameter feedback latency for the stated difference and the mean rating on the semantic differential are shown in Fig. 5. At a latency of 20 ms, 40 % of the test subjects noticed a difference to the reference stimulus without latency. At this value, a slightly improved rating trend can be observed, but this is not statistically significant. The 50% stated Difference is reached at a 50 ms latency. From this value, the rating also begins to fall continuously. 90 % of the test subjects already detect a 125 ms latency (M = 3.4, SD = 1.00), and all recognize a 250 ms latency (M = 3.0, SD = 0.94).

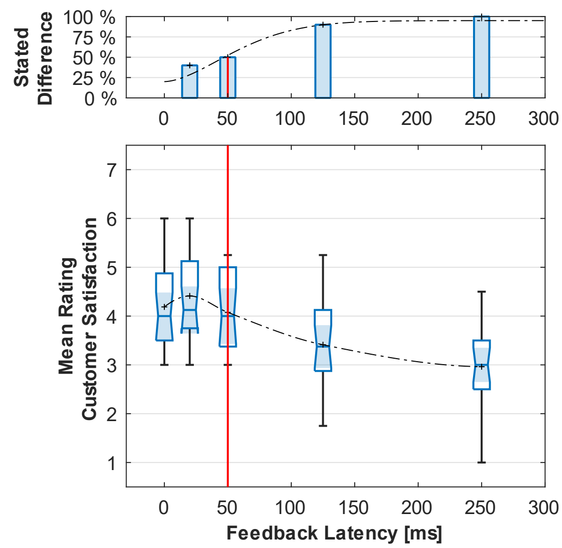

Fig. 5. Stated difference and mean rating of the customer satisfaction for the parameter feedback latency. The red line highlights the position of the 50 % stated difference at 50 ms. The parameters of the Weibull function according to [21] were defined as follows: $\gamma = 20$ % and $\lambda = 5$ % were assumed based on the study design, while $\alpha = 70$ ms and $\beta = 1.7$ were fitted to the data.

C. Feedback Reliability

The results for the parameter Missed Feedbacks are shown in Fig. 6. Almost all participants (95 %, 95 % and 100 %) reported a difference between the tested stimulus sets with missing feedbacks. Also, the sporadic missing release feedback (M = 2.6, SD = 1.04), the sporadic missing push feedbacks (M = 2.1, SD = 0.83), and the sporadic missing push & release feedbacks (M = 1.6, SD = 0.68) received the worst ratings of all stimuli sets tested, which are statistically significantly by 39 %, 49 %, and 62 % worse than those of the reference stimulus. In addition, the stimuli set with sporadic missing push and release feedbacks are rated statistically significantly worse than the stimuli set with only sporadic missing release feedback.

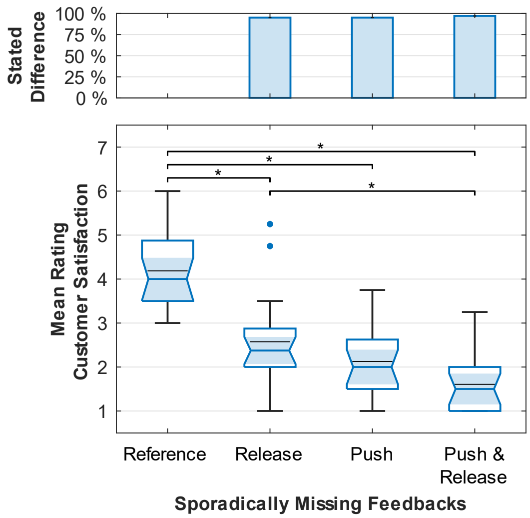

Fig. 6. Stated difference and mean rating of the customer satisfaction for the parameter feedback reliability.

D. *Variation of the Feedback Waveform*

Fig. 7 shows the results for the parameter Feedback Waveform. All subjects reported a difference between the stimuli sets tested for this parameter. No statistically significant differences in mean ratings were found between all three stimuli sets due to the more extensive scatter range of the stimuli sets with the medium stimulus (M = 3.5, SD = 1.31) and Long stimulus (M = 3.0, SD = 1.50). However, a trend towards a deterioration with increasing duration of the haptic feedback is recognizable.

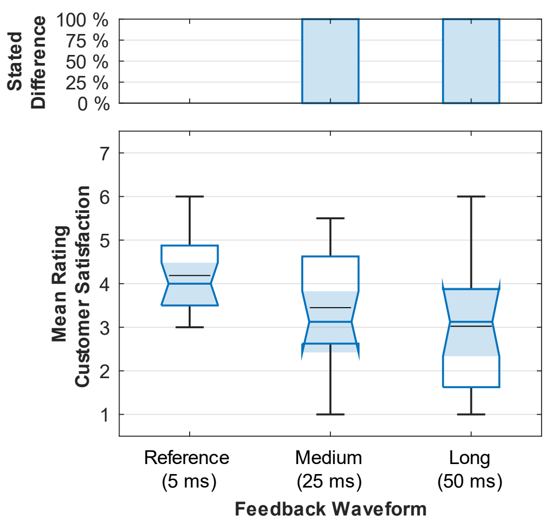

Fig. 7. Stated difference and mean rating of the customer satisfaction for the parameter feedback waveform.

E. *Variation of the Feedback Acoustics*

The results for the parameter Feedback Acoustics are presented in Fig. 8. All test subjects reported a difference between the tested stimuli sets as with the Feedback Waveform parameter. No statistically significant difference between the stimuli could be determined due to the extensive scatter range of the ratings. A trend towards a rating deterioration with increasing high-frequency acoustic components of the haptic feedback is recognizable for slightly tinny noise (M = 3.9, SD = 1.57) and tinny noise (M = 3.1, SD = 1.55).

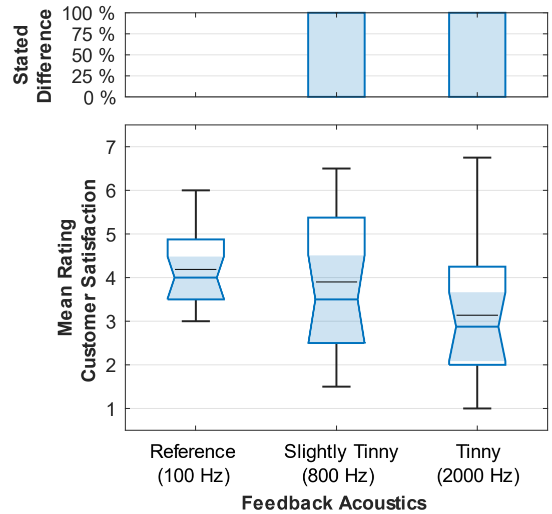

Fig. 8. Stated difference and mean rating of the customer satisfaction for the parameter feedback acoustics.

IV. Discussion

A precise understanding of the key parameters influencing user perception is essential for the systematic development of control elements with active haptics. The primary objective of this study was to investigate how variations in these parameters affect participants' subjective perceptions. The study aimed to establish a relationship between parameter deviations and perceptual thresholds by systematically assessing these variations. To achieve this, parameter sets were created with controlled variations and evaluated by participants. These variations were designed to reflect both the critical tolerances relevant during the initial specification of haptic feedback systems and typical fluctuations in manufacturing quality.

The results for the variation of the force threshold show that, based on the interpolation of the mean ratings, 50 % of the test subjects noticed a difference to the reference stimulus at ± 0.7 N. Furthermore, the result shows that as soon as a variation in the force threshold is perceived, it is also rated more negatively. The results for the feedback latency parameter are very similar. The latency after which the rating decreases also corresponds to the stimulus at which 50 % of the test subjects noticed a difference to the reference stimulus, which is 50 ms. This finding aligns with previous studies showing that latencies below 50 ms are generally perceived as instantaneous [15, 20] and with the work of Kaaresoja et al., who observed a significant decline in user satisfaction at varying latencies between 18 and 72 ms [20].

For the control element specification, the force sensors' tolerance should be below ± 0.7 N. In addition, the feedback latency must not exceed 50 ms for users to be detected. As a limitation of this result, it should be noted that both parameters interact in practice. A high latency can also appear as a high force threshold to the user. The faster the user presses the button, the higher the perceived force at which the feedback occurs. This means that not only should the force sensor not exceed ± 0.7 N, but the combination of latency and sensor accuracy must also be sufficient to provide feedback for the user within ± 0.7 N of actuation force.

Missing feedback is immediately perceived by subjects and generates significant dissatisfaction, which shows the negative rating of the stimuli set. The results highlight both the expectation and the necessity of haptic feedback for touch-based control elements. There are also differences between the stimuli sets with sporadic missing feedback. Missing Push- & Release-Feedback is significant more negatively rated compared to just missing Release-Feedback. One possible explanation is that users expect push feedback and tend to continue pressing while delaying finger lift until they perceive the push feedback. If the push feedback fails to trigger, frustration may arise. However, when they eventually lift their finger and still receive release feedback as confirmation, this could partially mitigate their dissatisfaction. In contrast, when release feedback is absent, users already receive confirmation upon pressing. As a result, the missing release feedback is noticeable but may not be as dissatisfying.

Variations in the feedback waveform and feedback acoustics were perceived comparatively easily by all test subjects. There are several possible reasons for this: As the specified stimulus durations indicate, the differences between them were very clearly perceptible. A finer gradation of stimuli might have led to different results. Also, humans are highly adept at detecting differences, especially when it comes to acoustics and vibrotactile vibrations on the fingertip. In contrast, the absolute perception of force at the fingertip is more challenging [22–24]. And the test subjects knew that they were taking part in a study on active haptic feedback and concentrated intensely on what they felt. The feedback waveform and acoustics are apparent factors compared to the parameters feedback latency and force threshold, which only technology enthusiasts tend to be able to classify.

The mean ratings for the tested variations in the feedback waveform and acoustics show a non-significant trend, with longer durations and a more tinny sound being rated more negatively, similar to the way experts would evaluate them. The findings towards waveform length are in line with studies on automotive controls [11] and smartphones [25, 26]. Notably, the scattering of the results for both parameters increases significantly with a higher variation. It seems that the test subjects do not have a clear common preference and struggle to evaluate haptic feedback in absolute terms. For the acoustics parameter, a second factor may also have influenced the result, which is that the additional high-frequency noise generally made the acoustic feedback louder, which may also have influenced the test subjects [27].

Feedback reliability in the analyzed parameter show the characteristics, that even when the system operates with perfect reliability, users remain neutral in their assessment. However, if the system fails to provide consistent feedback, it leads to significant dissatisfaction. By analogy with the KANO model, feedback reliability can be classified as a basic function, as customers expect it to work flawlessly and take it for granted. Similarly, the parameters force threshold and feedback latency also fall into the category of basic features. They are expected by users and only negatively impact perception once they exceed a certain threshold. While feedback reliability, force threshold, and feedback latency would likely be initially categorized as basic features by experts, feedback waveform and acoustics may be considered performance features. These features generate satisfaction when executed well and cause dissatisfaction when they do not meet expectations. However, the available data does not clearly support this classification. Instead, waveform and acoustics would more likely be assigned to the basic features category, as variations were noticeable but did not significantly impact ratings. Additionally, no alternative stimuli with potentially superior characteristics were tested against the reference stimulus, making it difficult to determine whether improvements in waveform or acoustics could lead to increased user satisfaction. [28]

V. Conclusion and Outlook

In Summary it appears most critical to focus on feedback reliability, as this factor will significantly worsen the subjective quality. Missing feedback must be avoided in any case. In practice, this means that a robust and reliable system must be developed as the basis for all other parameters. In terms of cost optimization, the actuation force threshold should not exceed ± 0.7 N, and the feedback latency should be kept within 50 ms as individual parameters. Additionally, the feedback should occur within the ± 0.7 N range of the force threshold. But there is no need to reduce it to an even lower magnitude, as only a small percentage of users are able to perceive these variations. In contrast, while waveform and acoustic variations are noticeable, they are not as impactful on overall user ratings as the feedback reliability and could potentially be prioritized lower in cost-sensitive design strategies.

The findings contribute to an informed trade-off analysis in the specification process, ensuring an optimized user experience while balancing production costs and system complexity. The data recorded in this study on the force-time curves of the actuation provide a reasonable basis for further analyses to understand the users' actuation behavior in a more differentiated way. They also enable the investigation of potential correlations between the varied parameters, the actuation behavior, and the perceived quality. It may be possible to identify correlations that identify central causes for particularly positive or negative ratings. One potential hypothesis from the results obtained in this study is that subjects who typically actuate very quickly notice the influence of high feedback latency much more and rate it worse than comparatively slow actuators. Future studies could also investigate the extent to which the control surface's force-displacement characteristics may cause other effects of the parameter variations and how they influence users' actuation behavior.

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