Factors on Vibrational Harm during Hammer Drilling

Influences of Lateral Force, Feed Force, Hammer Drill and Drill Bit Type

by *Michael Uhl[1], Jan Heinrich Robens[1], Marius Gauch[1], René Germann[1], Sven Matthiesen[1]

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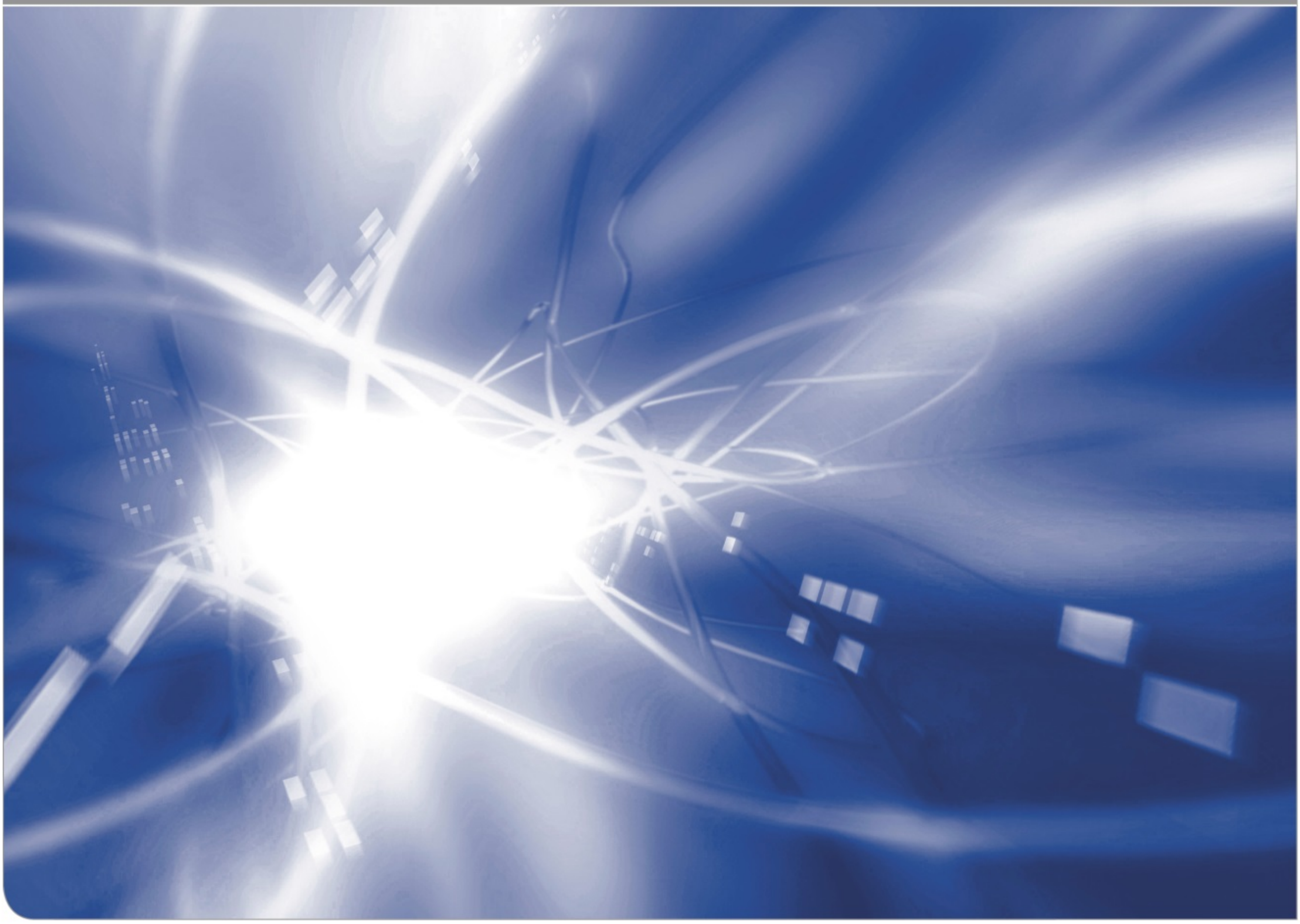

[1] Institut für Produktentwicklung, Karlsruher Institut für Technologie (KIT)
* Corresponding author

Impressum

Karlsruher Institut für Technologie (KIT)
www.kit.edu

2022

ISSN: 2194-1629

Factors on Vibrational Harm during Hammer Drilling – Influences of Lateral Force, Feed Force, Hammer Drill and Drill Bit Type

Abstract:
When using hammer drills, the user is exposed to vibrations which can cause damage to the body. Those vibrations can be affected by external factors such as feed forces, which can increase the degree of damage to the user. However, currently there is a lack of knowledge as to whether the lateral forces applied by the user also have an influence on the technical system and whether these influences depend on the system. For this reason, a study with 1152 test runs was carried out on a test rig to investigate the relationship between the feed force and the lateral force as a function of the hammer drill setup on the vibrations at the hammer drill housing and main handle. The experiment showed that the feed (p = < .001, up to r = 0.57) and lateral (p = < .001, up to r = 0.77) forces had an influence on the vibrations of the hammer drill. However, these depended strongly on the technical system and hence cannot be generalized. Furthermore, it was proven that the impact frequency of the hammer drill was reduced by increasing both the feed force (p = < .001, r = 0.55) and the lateral force (p = < .001, r = 0.23). The findings can not only be used by engineers and scientists to further develop vibration standards, but also to design more ergonomic hammer drills. Hence, the vibration decoupling of hammer drills should be redesigned so that lateral forces do not lead to an increase in vibrations that are harmful to the user.

Keywords: human factors, power tool, user forces, human machine system, vibrational diseases

Highlights:

- Lateral and feed force influence the vibration at the main handle and housing
- The influence of user forces depends on the hammer drill and drill bit combination
- Lateral forces should therefore be taken into account in standards determining a_{hv} values.

1 Introduction

Hammer drills are used in commercial construction to drill holes in concrete. An example of this would be to place anchors. The hammer drill is manually guided by a human, which results in a strong interaction of the two subsystems. If this human-machine system is observed from an ergonomic point of view, it becomes apparent that the weight of the hammer drill and the forces required for a stable operating process cause human fatigue (Anton et al., 2010; Blache et al., 2015). In addition, the dust, noise and vibrations generated during the working process also cause stress. If the system is to be developed specifically for optimized user experience in the sense of user-centered design, it is important to understand the relationships that lead to the negative effects. This way, the negative influences can be taken into account in product development. Various studies, which discuss the subject of vibration exposure to humans already exist. This includes studies that focus on any diseases that may arise (Bovenzi, 1994; Poole et al., 2019), as well as how the exposure can be measured (ISO 28927-10:2011, 2011) and reduced (Gillmeister, 1998; Golysheva et al., 2004; Hamouda et al., 2018; Hecker and Riederer, 1985; Oddo et al., 2004; VDI 3831, 2006). Passive vibration decoupling of the main handle has been established already, and can be found in many commercially available hammer drills. The efficiency; however, of these vibration decouplings of individual suppliers vary greatly, and should be further improved in order to reduce the strain on the user. This variance stems from the fact that not all relationships between the user and the system during use are sufficiently understood. The current state of research shows that the user forces in particular have a decisive influence on the vibrations.

Various studies have shown that the feed force has a strong influence (Botti et al., 2020; Uhl et al., 2019) on the housing vibration. This influence can vary depending on the hammer drill (Cronjäger and Jahn, 1985; Rempel et al., 2019a; Schenk and Knoll, 1998) and drill bit (Cronjäger and Jahn, 1985; Jahn, 1985), and hence cannot be generalized. Whereas pneumatic hammer drills were commonly used in the past, they are now being replaced by electropneumatic hammer drills in small and medium-sized hammer drills. Further distinguishing features of hammer drills are the impact energy and design of the percussion mechanism. In addition to the classical drill bits with helix, hollow drill bits are increasingly used. The hollow drill bits reduce the dust exposure of humans (Rempel et al., 2019b). Whether the beforementioned influence has an effect on the hammer drill vibrations has not been described in the state of research so far. Uhl et al. (2021; 2019) further demonstrated that in addition to the feed forces of the user, lateral forces are also applied unintentionally. In the aforementioned studies, the forces were in the range between 4.7 N and 73.1 N. This finding is confirmed by the description of occurring transverse motion of the drill bit due to the human behavior, by Momeni et al. (2017). The influence of these lateral forces have not been investigated to date in the current state of research. Cronjäger et al. (1984); however, points out that an insufficiently aligned hammer drill leads to negative influences on the resulting vibrations.

Therefore, this study will investigate the relationship between the lateral forces and feed forces with the dependent variable housing vibration.

In order to find out about these correlations, different feed and lateral forces were adjusted on a robot-based test rig. Their influence on the housing vibration was investigated. Since the behavior depends on the hammer drill as well as on the drills, two hammer drills and three drill types were investigated.

2 Materials and methods

2.1 Experimental setup

In this experiment, two kinds of hammer drills were used. A hammer drill from Bosch (model GBH 3-28 DFR, Robert Bosch Power Tools GmbH, Leinfelden-Echterdingen, Germany) had a percussion mechanism with an angular gear and a sewing bearing to realize the impact. The vibration value was given as 14.5 m/s² and the single impact energy was 3.1 J according to the manufacturer. The second hammer drill from Hilti (Modell TE 30-AVR, Hilti Deutschland AG, Kaufering, Germany) had a percussion mechanism with a connecting rod drive. The vibration value was given as 10±1.5 m/s² and the single impact energy was 3.6 J according to the manufacturer. Both hammer drills had a SDS-Plus chuck. In total, three different drill bit models were used. A helical drill bit from Hilti (model TE-CX 10/22 MP8, Hilti Deutschland AG, Kaufering, Germany) had a diameter of 10 mm and four cutting edges. The second model was a drill bit created by ALPEN-MAYKESTAG (model SDS-plus F4 Forte, ALPEN-MAYKESTAG GmbH, Puch, Austria), with two cutting edges. It also had a diameter of 10 mm. Furthermore, a hollow drill bit with two cutting edges and a diameter of 14 mm was used (Modell FHD 14/250/380, fischerwerke GmbH & Co. KG, Waldachtal, Germany). The 10 mm diameter drill bits were selected to compare the results obtained on the test rig with those obtained in a manual study (Uhl et al., 2021). However, since a hollow drill bit was to be investigated in addition to the two helical drill bits and this was only available from 14 mm diameter, a larger diameter had to be selected. In this study, the results of the individual drill bit types were not directly compared with each other, but only the qualitative progressions. A standardized concrete with C20/25 (concrete test body C 20/25, Rau-Betonfertigteile, Ebhausen, Germany) with a minimum compressive strength of 25 N/mm² and the dimension 2145 mm x 1200 mm x 200 mm were utilized. The concrete block cured at least 28 days.

The experiment was carried out on an automated test rig with an industrial robot (see position 1 in Figure 1 model KR 500 R2830 MT, KUKA, Augsburg, Germany). The hammer drill (4) was mounted to the flange of the robot using a hand-arm model (6) based on (Cronjäger et al., 1984; Jahn and Hesse, 1986), as well as a multi-axis force torque sensor system (see position 2 in Figure 1, model NET FT Omega 160-IP65, ATI, Apex, NC, USA). An exhaust system (3) was used to remove the dust from the air. A vacuum cleaner from Festool (Absaugmobil CLEANTEC CTL 26 E, Festool GmbH, Wendlingen, Germany) was used for hollow drill bits. The setup of the test bench as well as the coordinate system are shown in Figure 1.

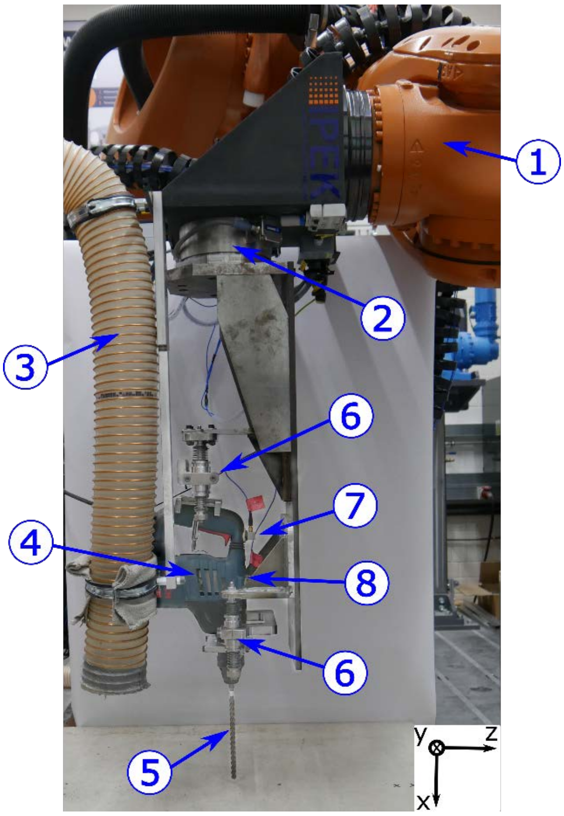

Figure 1. Robot-based automated test rig for hammer drilling into concrete

Two accelerometers (model 356A02, PCB Piezotronics, Depew, NY, USA) were used to measure the hammer drill vibrations. The first accelerometer (7) is located at the position defined for the main handle in ISO 28927-10 (2011). Since the hand-arm model used inhibited the side handle to be mounted, the second accelerometer (8) could not be positioned at the position defined in the standard, and was instead mounted on the hammer drill housing near the side handle position. Furthermore, two temperature sensors (TJC100-ICSS-M050U-150, OMEGA Engineering GmbH, Deckenpfronn, Germany) were used to measure the hammer drill and drill bit tip temperatures. The temperature of the hammer drill was measured at the housing of the hammer mechanism. A real-time system (ADwin-Pro II, Jäger Computergesteuerte Messtechnik GmbH, Lorsch, Germany) was utilized to acquire the data with a sampling frequency of 12500 Hz.

2.2 Experimental design and procedures

To save time and to avoid unnecessary failures due to changes at the test rig, the hammer drill and drill bits were considered as blocks. A full factorial randomized experimental design was performed for the feed and lateral force using MODDE (MODDE 12, Umetrics, Sweden). This experimental plan was applied for each drill bit and was replicated three times. For every replicate, a new drill bit was used. After all test runs of the first hammer drill were performed, the second hammer drill type was used. With each drill bit, 48 boreholes were drilled (1152 runs in total). Each borehole was drilled vertically downwards with a depth of 120 mm. In order to prevent possible binding of the drill bit due to lack of air flushing, a drill bit retraction phase was carried out at half the depth of the borehole. During runs with the hollow drill bit, the vacuum cleaner was used to remove the drilling dust. The positions of the boreholes were randomized on the concrete block. This reduced a possible influence of the inhomogeneity of the workpiece characteristics caused by the manufacturing process. During the drilling, no reinforcing iron was hit. The factors and their factor levels are listed in Table 1.

Table 1: Factor levels of the analyzed variables

FACTOR	**FACTOR LEVEL**					
Feed force [N]	80	110	140	170	200	230
Lateral force [N]	0	20	40	60		
Hammer drill	Hilti TE 30	Bosch GBH 3-28				
Type of drill bit	D10 2 cutting edges	D10 4 cutting edges	D14 2 cutting edges			

During the experiment, the hammer drill was switched on after approaching the workpiece via a power supply control. In order to avoid a possible influence of the hammer drill and drill bit temperature on the results, a warm-up phase of the hammer drill before the experiment and a cooling phase of the drill bit between each test run were carried out. Thus, the drill bit repeatedly cooled down to 60 °C between each drilling. Based on the pre-study, a warm-up phase during which the hammer drill was switched on lasted at least eight minutes to reach a nearly constant. The temperature of the hammer drill was between 80 and 90 °C during drilling, because a low operating temperature of the hammer drill can have a negative influence on its behavior (Cronjäger and Jahn, 1985).

While drilling, the robot system applied constant feed and lateral forces due to a force control. For realization of the control, a Proportional Integral (PI) control was used for the feed force and a Proportional (P) control for the lateral force. To prevent the drill bit from breaking out to the side, the lateral force was applied from a drilling depth of 30 mm. The lateral force was applied in the y-direction (see Figure 1) of the tool coordinate system. The lateral force in the z-direction was controlled to 0 N after 30 mm of drilling depth.

2.3 Data analysis

Only the range of constant drilling conditions were evaluated. Therefore, data sets were cut to the range where the target feed and lateral forces were achieved using MATLAB (R2017b, The MathWorks, Natick (Massachusetts). The evaluation range thus varies for each test run, but always exceeds the minimum duration of 8 s specified in ISO 28927-10 (2011). In the next step, the dependent variables were calculated from the acceleration data. To evaluate the harm of the user by the vibrations, the a_{hv} value was calculated for both accelerations according to ISO 28927-10 (2011) and ISO 5349-1 (2001). In order to be able to evaluate what caused the different a_{hv} values in the device, the comparison of time signals of the acceleration helped. For this purpose, the vibration data was first filtered. This was done with a 4th order Butterworth low pass filter that has a cut-off frequency of 500 Hz. Finally, in order to better understand the influence of the user forces on the vibrations, Fourier transformations were performed to be able to determine the change in the impact frequency.

Moreover, statistical analysis was performed using SPSS (IBM SPSS Statistics 25, IBM, Amonk, NY, USA). In the first step, it was examined whether the boundary conditions for parametric tests were fulfilled. However, since this was not the case (e.g. no normal distribution and equality of variance of the subgroups), the Kruskal-Wallis test was performed to verify whether the feed force and lateral forces have an influence, and whether this occurs in all hammer drill setups. Median (Mdn) and interquartile ranges (IQR) are given in the chapter ‘Results’. P values < .05 were considered significant.

3 Results

Before the actual evaluation, it was checked whether the results obtained with the test rig were comparable with the manufacturer's data. The tests for determining the a_{hv} value according to the standard (ISO 28927-10:2011, 2011) are carried out at approximately 110 N and a diameter of 16 mm for these two types of hammer drills. Because of this, only the hollow drill bit with a diameter of 14 mm, FF = 110 N and LF = 0 and 20 N were used for the comparison. Under the beforementioned conditions, a median with the a_{hv} value of Mdn = 14.3 m/s² and IQR = 1.2 m/s² was determined for the GBH 3-28, and a median of Mdn = 9.4 m/s² and IQR = 1.8 m/s² for the TE 30. Hence, a deviation of 0.2 m/s² (GBH 3-28) and 0.6 m/s² (TE 30) from the manufacturer's specifications were observed.

Analysis of the influence of feed force on the drilling process

The impact frequency of hammer drills is directly coupled to the motor speed by the drive train. The variances of the impact frequency of both hammer drills at FF = 80 N and 230 N do not differ significantly and thus homogeneous variances can be assumed, as shown by Levene's test via t-test, respectively ($F(1,381) = 0.138$, $p = < .711$, $n = 383$). Using the t-test, it was shown that the impact frequency changed significantly $t(381) = 12.952$, $p = < .001$. Cohen's (1992) effect size is $r = 0.55$, corresponding to a strong effect. As it can be seen in Figure 2, the impact frequency of both the TE 30 and GBH 3-28 decreased linearly by about 4 Hz when the feed force was increased. The TE 30 has an impact frequency of Mdn = 71.7 Hz at 80 N feed force, and decreases to a value of Mdn = 67.7 Hz at 230 N. The GBH 3-28 has a generally lower impact frequency of about 3.5 Hz and decreases from Mdn = 68 Hz (80 N) to Mdn = 64.3 Hz (230 N).

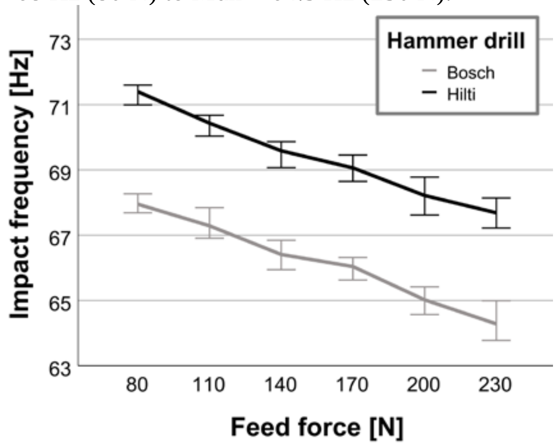

Figure 2. Influence of feed force on impact frequency for each hammer drill. The data includes all analyzed drill bit types (n = 1152).

Figure 3 shows the influence of the feed force on the a_{hv} value at the housing and main handle. A distinction was made between the two hammer drills and the individual drill bit types. It can be seen that for the **GBH 3-28**, the a_{hv} value on the housing decreased linearly with increasing feed force. It was proven in this study that there was a large effect for the hollow drill from 80 to 230 N and a medium effect for the helical drill bits. On the main handle; however, an influence of the feed force on the a_{hv} value could only be demonstrated for the helical drill bit with two cutting edges. Here, a medium effect was seen. As can be seen in Figure 3 on bottom left, the course of the helical drill bit with two cutting edges has a quadratic course, with the maximum of 16 m/s² at a feed force of 170 N. The drill bit with four cutting edges also showed a downward opening quadratic trend, whereas the trend seemed to decrease for the hollow drill. These effects; however, could not be statistically proven.

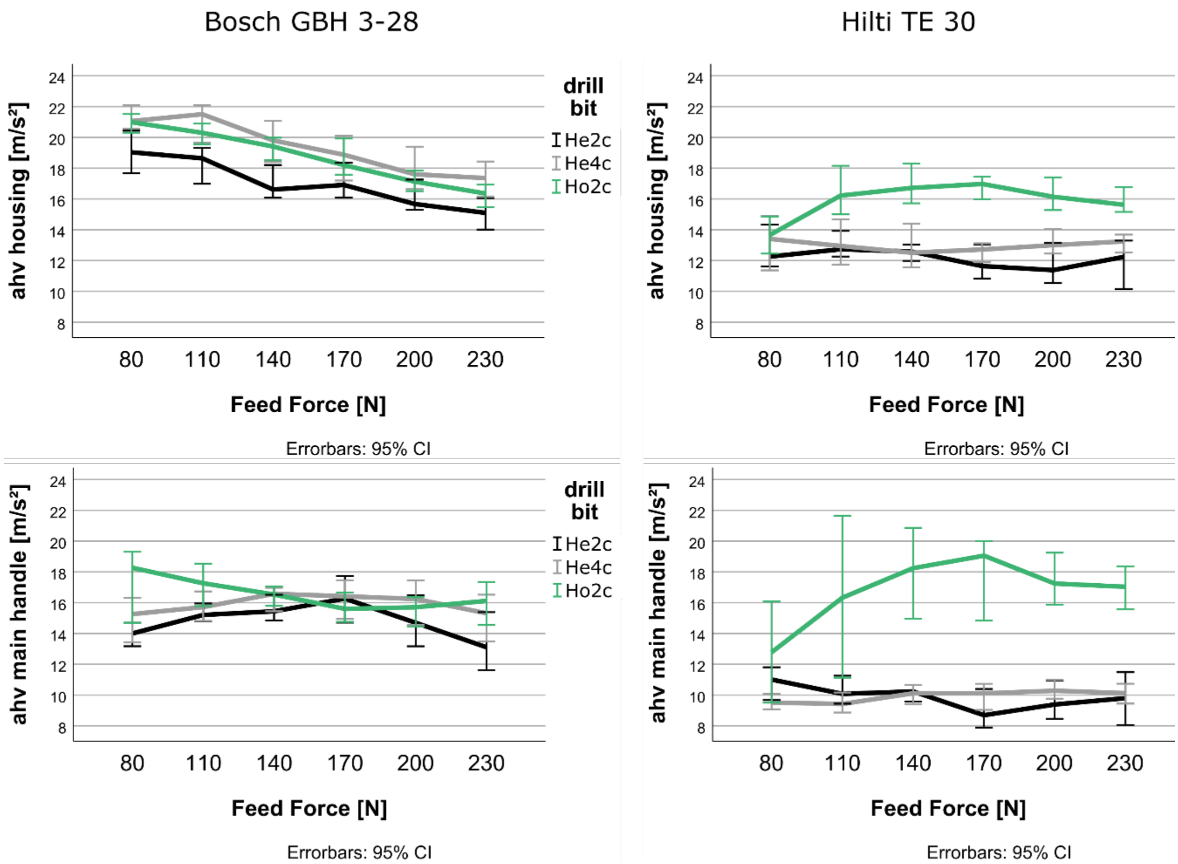

Figure 3. Influence of feed force on a_{hv} value of the housing and the main handle for each hammer drill and drill bit. n = 1152.

For the **TE 30**, the drill bit types on the housing produced a different course of the a_{hv} value. For the drill bit with four cutting edges, no effect of the FF could be detected. Additionally, a median of 13 m/s² was observed for all FF. For the helical drill bit with two cutting edges, only a small effect between 110 N and 170 or 200 N could be detected. The a_{hv} value curve has an undulating course. For the hollow drill bit, a difference between 80 N (Mdn = 13.7 m/s²) and the other feed forces (Mdn = 16.3 m/s²) was demonstrated. Here, a medium effect occurred. As with the housing, no difference can be demonstrated for the main handle by varying the feed force for the drill bit with four cutting edges. The median over all FF was 10 m/s². For the helical drill bit with two cutting edges, a v-shaped trend can be seen. However, only a small effect between 80 N and 170 N could be detected. In the case of the hollow drill bit, the relative course of the curve is comparable to that of the housing. Except for 80 to 230 N, a difference between 80 N and the other feed forces was also demonstrated. According to Cohen (1992), this was equivalent to a small effect due to the high scatter. In contrast to the other setups, a very high scatter occurred for the hollow drill bit, which becomes comparable to the other drill bit types at 200 N and in particular at 230 N.

Figure 6 shows the low-pass filtered time signals of the housing vibration (black line) and main handle vibration (green line) of the helical drill bit with four cutting edges in the x-direction. The first six diagrams show the signals of the GBH 3-28 at different feed forces and the other nine diagrams for those of the TE 30. Since the diagrams in Figure 3 show that the a_{hv} values differ drastically for the TE 30 with hollow drill bit, the related time signals have also been shown in Figure 6 (bottom row). For a better understanding, the impacts known from the state of the research have been marked in the individual diagrams by the corresponding abbreviations. The known impacts occur as listed in the following: when the housing or damping element hits the striker pin due to the pressing force applied by the user (B), when the air spring is compressed due to the forward movement of the drive piston (SA), and due to the rebound of the striker pin after the impact (ZK). The ZK-impact can be caused either by the impact of the striker pin on the damping element or due to its own impact on the striker piston. When comparing the time signals of the two hammer drills, it is noticeable that the three known impacts in the signal from the GBH 3-28 are superimposed by other vibrations. Furthermore, it was observed that, in contrast to the GBH 3-28, the

B-impact hardly occurred with the TE 30 at a feed force of 80 N. At 110 N, the B-impact occurred alternately and became stronger with increasing FF. The increasing B-impact and its earlier occurrence in the impact cycle was also evident with the GBH 3-28. A clear decrease in the ZK-impact was also seen here. In the time signals on the main handle, it was noticeable that the SA-impact was barely visible on both hammer drills. The B-impact also increased at the main handle on both, but especially on the TE 30, hammer drill. In the diagrams of the hollow drill bit, it can be seen that at FF = 80 N, the B-impact hardly occurred. If FF was increased to 170 N, both B, SA and ZK become significantly stronger. This is clearly more evident than for the helical drill bit with four cutting edges. At FF = 230 N, the three impacts decreased again but were still significantly higher than at 80 N, except for SA.

Analysis of the influence of lateral force on the drilling process

The variances of the impact frequency of both hammer drills at LF = 0 N and 60 N differ significantly. Thus homogeneous variances cannot be assumed, as shown by a test using a Levene's test via t-test, respectively ($F(1,573) = 6.968$, $p = .009$, $n = 575$). Using the Welch test, it was proven that the impact frequency changed significantly $t(549.800) = 5.431$, $p = < .001$. Cohen's (1992) effect size is $r = 0.23$, corresponding to a weak effect. When the lateral force was increased in the test runs, the impact frequency (see Figure 4) decreased. Without an applied lateral force, the TE 30 had an impact frequency of Mdn = 70 Hz and decreased by 1.7 Hz (60 N) when the lateral force was increased. The GBH 3-28, on the other hand, had an impact frequency of 66.8 Hz at 0 N and decreased by 1.5 Hz.

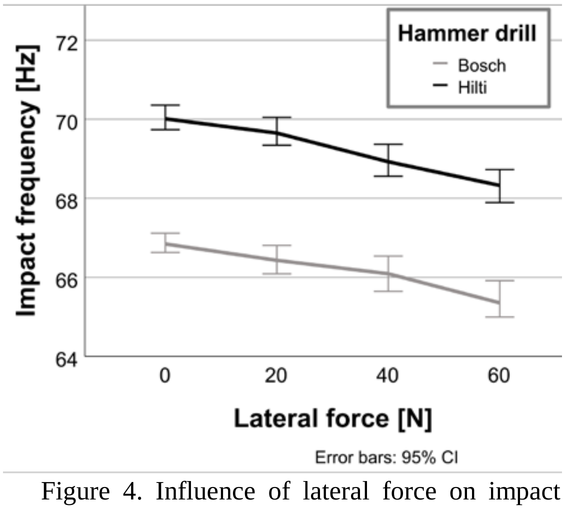

Figure 4. Influence of lateral force on impact frequency for each hammer drill. The data includes all analyzed drill bit types. n = 1152.

The influence of the lateral force on the a_{hv} value is shown inFigure 5. Here, a distinction has also been made between the hammer drills and the three drill bit types. The a_{hv} value at the housing of the **GBH 3-28** of the three drill bit types behaved very similarly when lateral forces were applied (Figure 5, top left). Initially, the a_{hv} values appeared to increase for all drill bit types, although this could not be statistically proven (Table 5). Subsequently, the curves drop. In the case of the hollow drill bit, no influence of the lateral force could be demonstrated on the housing. For the helical drill bit with two cutting edges; however, a medium effect with $r = 0.46$ was seen. Furthermore, the drill bit with four cutting edges demonstrated an even a strong effect, with $r = 0.6$. In contrast to the housing, the a_{hv} values at the main handle increased for all drill bits (Figure 5, bottom left). The a_{hv} value at the hollow drill bit increased across all applied lateral forces, with no detectable increase between 40 and 60 N, showing a strong effect with $r = 0.7$. For both helical drill bits, a linear increase occurred between 0 and 40 N. Between a lateral force of 40 and 60 N, the a_{hv} value seem to decrease slightly again. This; however, could not be proven statistically.

The a_{hv} value on the housing of the **TE 30** (Figure 5, top right) was not influenced by the lateral force in the helical drill bit with two cutting edges (Mdn = 12.3 m/s²). The course of the hollow drill bit is similar to that of the hammer drill from Bosch, but only a difference between a lateral force of 0 N and 20 N and a minor effect ($r = 0.26$) could be shown. For the helical drill bit with four cutting edges, the a_{hv} value decreased with the increase of the lateral force. The strongest decrease was found between 20 and 40 N. The effect strength of $r = 0.56$, which is a strong effect, resulted from LF = 0 to 60 N. At the main handle, the vibration values increased as with the GBH 3-28. The increase for the two helical drill bits seems to be comparable (see Figure 5, bottom left). For the helical drill bit with two cutting edges, the jump was largest between 20 and 40 N, but only between 0 and 60 N a small effect of $r = 0.21$ was detected. For the drill bit with four cutting edges, a medium effect ($r = 0.41$ from 0 to 60 N) was observed. The largest rise between 20 and 40 N corresponded to a small effect strength of $r = 0.27$. In contrast to the helical drill bits, the a_{hv} value of the hollow drill bit changes more strongly ($r = 0.71$).

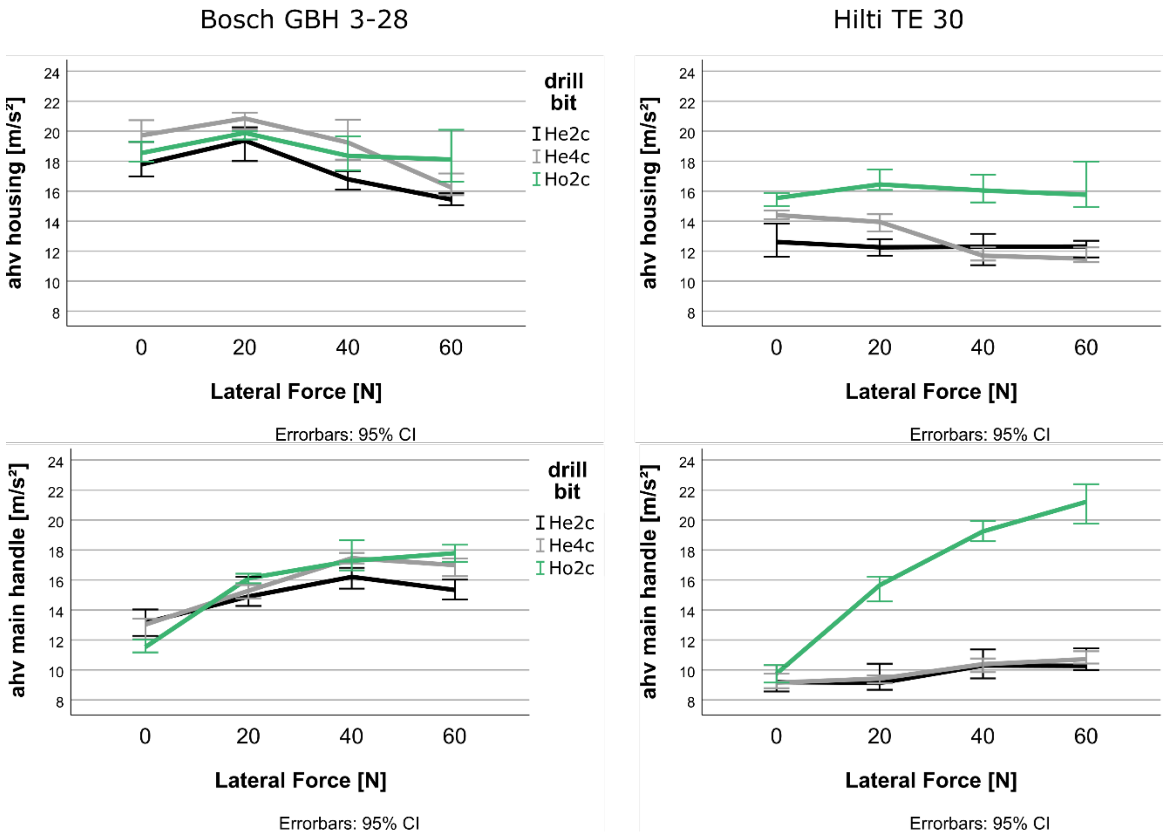

Figure 5. Influence of lateral force on a_{hv} value of the housing and the main handle for each hammer drill and drill bit. n = 1152.

Figure 7 shows the exemplary time signals of the housing (black line) and main handle vibration (green line) in the x-direction. In the diagrams for two impact cycles, the known impacts B, SA and ZK were marked. Here, the signals of the two hammer drills, upper two rows GBH 3-28 and lower three rows TE 30 are shown. The respective upper rows of the hammer drills show, as an example, the change due to the lateral force at FF = 110 N and the lower one at FF = 170 N. Since the diagrams in Figure 4 show that the a_{hv} values differ drastically for the TE 30 with hollow drill bit, the related time signals have also been shown in the Figure 7 in the bottom row. At 110 N, it can be seen in the signal on the TE 30 at the housing that the B-impact increased to higher lateral forces. These effects can be observed on the main handle both at 110 N and at 170 N, with the ZK impact also increasing strongly. At 170 N, LF = 40 and 60 N SA can still be easily recognized. The increase in the B-impact on the main handle also takes place on the GBH 3-28. In the case of the hammer drill from Bosch, an additional impact, which is reduced at the main handle, has increased between the B and SA. This effect is not yet described in the state of research. In the diagrams, which show the time signal of the TE 30 with hollow drill bits, it can be seen that at the housing (black line) SA increased. Additionally, in the area of ZK, more vibrations can be seen. The curves of the main handle show very clearly that B and ZK increase strongly.

4 Discussion

The aim of this study was to investigate the relationship between the feed and lateral forces on the hammer drill vibrations in the form of the a_{hv} value. Since there are different findings in the state of research on the relationship between the a_{hv} value and the feed force, this relationship was investigated for different hammer drill/drill combinations. It was found that the lateral force has an influence on the housing vibrations. Furthermore, it could be proven that this correlation as well as the influence of the feed force also depends on the choice of the technical system.

When comparing the a_{hv} values determined on the test rig in this study with the manufacturer's specifications, it was found that they match very well. In particular, the results with the 110 N feed force or low lateral forces are very comparable. It can be assumed that the manufacturers had applied a feed force of about 110 N during the tests to determine the a_{hv} value according to standard 28927-10 (2011). From this, it can be concluded that the test rig generated realistic results, particularly in the direction of impact, and thus are very well comparable with manual tests.

When evaluating influences on the a_{hv} value, considering the time signals of acceleration (Hecker and Riederer, 1985) is helpful. The TE 30 hammer drill from Hilti showed lower amplitudes, in particular it showed fewer higher-frequency oscillations both on the housing and on the main handle than the GBH 3-28 hammer drill from Bosch. This makes an evaluation of the signals and thus the influences on the a_{hv} value much easier. The fundamentally lower a_{hv} values and amplitudes in the time signal of the TE 30 are due to the greater mass and weight of the hammer drill. It can; however, also be caused by the different concepts for vibration reduction. In both hammer drills, the impacts in the acceleration signal known from research (Riederer, 1985) and characteristic for electro-pneumatic hammer drills can be recognized. First, the drill hammer housing hits the striker pin (B-impact). It then causes a compression of the air spring (SA), which finally causes an impact due to the rebound of the impact components (ZK). This can be transmitted either via the damping element or the air spring to the housing of the hammer drill. Which case occurs depends strongly on the weight ratio of striker piston, striker pin, and tool. The ratio of striker piston to striker pin is 1.59 for the TE 30 and 0.73 for the GBH 3-28. Furthermore, the GBH 3-28 has an additional mass of 23.7 g, into which the striker pin can strike. Based on the laws of conservation of momentum, it can be concluded that due to the lighter striker pin on the GBH 3.28, impact processes occur whereby the striker pin flies back and forth several times between the tool and the housing or the striker piston (Riederer, 1985). This could also lead to the multiple impacts in the range of ZK. The lighter striker pin further favors that the pressure waves induced from the concrete to the drill bit are transmitted to the housing. These pressure waves are generated by the elastic deformation of the concrete (Hecker, 1983).

When looking at the influence of the **feed force** on the a_{hv} value at the **housing**, it becomes clear that its influence strongly depends on the system. This can be explained by the stiffening of the hand-arm system due to the feed force (Marcotte et al., 2005). In the case of the hammer drill from Bosch, the a_{hv} value decreases almost linearly for all drill bits. Here, there are relatively small deviations between the individual drill types. The time signals show that the ZK was initially very high and continued to decrease due to the stronger coupling. This could be due to the increased mass coupling of the handle, and in particular the hand-arm system. Furthermore, it was observed that the B-impact increases slightly as the hammer drill is pressed more strongly by the user. As a result, the hammer drill no longer lifts off the concrete with a strong impact, which means that the hammer drill touches down again sooner. This can be observed at the time interval between B and SA. Another reason for the decrease in the a_{hv} value could be that there is too much drilling dust in the borehole, which increases friction and causes the drill bit to hit the drilling chips (Hecker, 1983).

On the other hand, in the case of the Hilti hammer drill, the three drill types caused a different behavior of the a_{hv} value. For the helical drill bit with four cutting edges, the B-impact, which was not visible at 80 N or alternated at 110 N (Riederer, 1985), increased with higher FF. In return; however, the pulse duration of the impacts of ZK became shorter. Thus, no influence of FF on the a_{hv} value could be demonstrated for this case. The a_{hv} values, when increasing the feed force for both drills with two cutting edges, first increased and subsequently decreased or increased again for the helical drill bit with two cutting edges at higher feed forces. In the time signal of the hollow drill it can be seen that B, SA and ZK increased extremely, and at 230 N decreased again. The very strong superelevation at 140 and 170 N could have been caused by a detuning of the percussion mechanism.

When looking at the influence of the feed force on the a_{hv} value at the **main handle**, the two hammer drills showed a qualitatively different course. Oddo et al. (2004) showcased through using different grip decouplings on a shaker-based test rig, that both the type of vibration decoupling and the contact pressure have an influence on the vibration behavior. Further studies (Aldien et al., 2005; Marcotte et al., 2005) show that the mechanical impedance of humans increases due to the pressure force. The different a_{hv} curves of the two hammer drills must therefore result from the interaction between the technical system and the feed force. In the case of the TE 30, the a_{hv} values behaved almost identically to those at the housing in relative terms, but are greatly reduced in the case of the two helical drill bits. In the case of the hollow drill bit, the vibrations at the main handle sometimes even exceeded those at the housing. The greater dispersion in the hollow drill bit resulted from the strong influence of the lateral force. At lower FF, the largest dispersion was present, which presumably resulted from alternating B-strokes (Riederer, 1985). These occurred continuously at higher FF, which resulted in the scatter becoming significantly smaller.

For the GBH 3-28, the a_{hv} value initially increased for all helical drill bits. This increase can be explained by an increase in ZK and the B-impact, due to the increased feed force. In particular, for the helical drill bit with two cutting edges, the a_{hv} value dropped again at higher feed forces. As can also be seen in the data for the drill bit with four cutting edges, ZK and B decreased at higher feed forces. This occurrence could be caused by the drilling dust in the borehole (Hecker, 1983), as speculated before already.

When looking at the influence of the **lateral force** on the a_{hv} value at the main handle and housing, it becomes clear that the relative curves of the two hammer drills are largely comparable. At the **main handle**, the a_{hv} value increased due to an increase in the lateral force. Looking at the raw signals, it can be seen that this resulted from the higher amplitudes of the ZK impact as well as the B impact. This behavior can be explained by the fact that although the handle is vibration decoupled with respect to the feed forces in the drilling direction, the decoupling does not work with respect to lateral forces. If lateral forces were now applied, the vibration decoupling would be bypassed and the main handle would couple more firmly to the hammer drill housing. This means that the vibrations could be transmitted more effectively. Through the beforementioned explanation, the opposite effect on the hammer drill **housing** can be described as well. Although the a_{hv} value initially increased when lateral forces were applied to the GBH 3-28 and to the hollow drill in combination with the TE 30, the a_{hv} value decreased as the lateral forces increased. The increase can be explained by the higher post vibrations in the area of ZK. So far, no studies investigating the influence of lateral forces on the mechanical impedance of humans are known. However, it can be assumed from the results that as with the feed force, an increase in the lateral force leads to an increase in impedance. This connects more mass to the housing, which reduces vibrations. To explain the decrease time signals, it can be seen from the vibration curve that neither the B-impact nor the SA-impact changed decisively. However, in the case of the hammer drill from Bosch, the intermediate impact (between B and SA) was greatly reduced. Additionally, in the case of the hammer drill from Hilti, the 3rd peak of ZK decreased greatly. This could be due to the bypass of the vibration decoupling or stiffer connection, whereby more mass of the main handle and especially the hand-arm model is coupled to the hammer drill housing (two-mass transducer). When comparing the drill bit types on the TE 30, it is clear that the two helical drill bits of comparable weight and length behaved very similarly. The steeper curve for the hollow drill bit perhaps resulted from the higher a_{hv} values at higher feed forces. As with the helical drill bits, the application of lateral forces bypassed the vibration decoupling. Thus, with the higher a_{hv} values due to FF, the a_{hv} values due to LF also increased.

The results of the **impact frequency** analysis show that by increasing the feed force, the impact frequency decreases for both hammer drills. This behavior was already shown by Jahn et al. (Jahn, 1985). The reason for this, as also suspected by Jahn et al, is the contact of the drill tip with the concrete. The higher feed force causes the hammer drill, and thus the drill bit, to lift less (Kivade et al., 2015). The friction between the drill tip and the concrete as well as the drilling chips increases the torque, which in turn reduces the motor speed (Hecker, 1983). Another reason for this can be explained by the higher feed rate and the associated increase in the amount of drill dust or cuttings to be removed.
Even with an increase in the lateral force, it can be observed that the impact frequency decreases with both hammer drills. A possible explanation, on the one hand, could be the higher friction of the drill shank in the borehole rim. On the other hand a tilting of the drill bit due to the bending moment leading to an increase in torque, could be a plausible cause as well. Since there is a difference in the impact frequencies per drill type even though the pitches are comparable, the difference should be related to the influence of the feed force or with the additional drilling feed.

To the best of the authors' knowledge, the investigations carried out in this study with regard to the lateral force has not yet been demonstrated in any other scientific study. The study showed that an increase in the lateral force increased the a_{hv} value on the main handle, but that the opposite was true for the housing. It was observed that the relationship between the lateral forces as well as the feed forces is strongly dependent on the system. Since the user applies lateral forces, especially in the field, these should be taken into account in the standards for determining the hammer drill-specific a_{hv} value. For example, specific tests could be conducted with and without lateral forces. As shown earlier, the relationships between the user forces and the vibrations are different for each hammer drill setup. Based on this, it should be analyzed whether this primarily depends on the type of grip decoupling or on the overall system. Here, it would be exciting to conduct further investigations with different devices from the two manufacturers with identical vibration decoupling concepts.

However, the knowledge gained can also be used by the manufacturers themselves. For example, it can be used for the user-centered development of hammer drills, which takes into account the occurrence of lateral and feed forces in the individual system, and are thus optimized accordingly. Here, the reduction of the a_{hv} value could perhaps be the goal. One approach could be to integrate elastomers in the transverse direction at the coupling of the main handle. However, it must still be ensured that the hammer drill can be guided in a stable manner by means of the main handle (Gillmeister, 1998). Acceleration sensors, most of which are already built into hammer drills, could also be used to determine the a_{hv} value during operation, and if these increase, feedback could be given to the user as to which of the user forces should be reduced. This should already be possible by knowing which vibration characteristics occur at different forces.

Limitations

The findings explored in this study were made using only two hammer drills and three drill bit types. In order to investigate further influences or dependencies between the technical system and the lateral force on the a_{hv} value, other hammer drill/drill bit setups should be investigated, e.g. also with other drive concepts. Furthermore, the hollow drill bit used here had a different diameter, since no hollow drill bit with a diameter of 10 mm is known on the market to date. This meant that it was only possible to a limited extent to distinguish between the influence of the hollow drill bit and the diameter used here. Thus, measurements with the same diameter between helical and hollow drill bits should be carried out in the future.

Furthermore, it should be explored where the findings obtained on a test rig can be transferred to humans. It is important to note that a hand-arm model, which reproduces the translational vibration characteristics in the impact direction of a human very well, was used here. It was not designed with regard to the transverse direction. It does; however, possesses the similarity with humans in a way that it stiffens when lateral forces are applied. Hence it is unclear how much the exact vibration characteristics differ in the transverse direction. Because of this, boundary points of the conducted experimental plan of the investigation should be carried out with a human. If it turns out that the vibration characteristics differ more clearly, a hand-arm model should be developed which simulates the user vibration characteristics both in the direction of impact and in the transverse directions.

5 Conclusion

This paper presents results of a test rig investigation of hammer drilling in concrete. In addition to the feed and lateral force, the hammer drill and the drill bit type were varied. The general aim was to analyze the influence of the user forces on the housing vibrations. The experiments conducted help engineers and scientists to develop more ergonomic hammer drills and design standards for determining the ahv value, which in turn produces more realistic and reproducible results.

The vibration values determined on the test rig are consistent with both manufacturer specifications and manual studies using the same hammer drill bit setup. The results of the study show that both feed and lateral forces have a significant effect on housing vibration for all setups. The determined correlations of user forces and housing vibrations differed depending on the hammer drill and the drill bit and are therefore not directly transferable. Furthermore, an increase in the user forces led to a decrease in the impact frequency of the hammer drill. It can thus be concluded that the user has a strong influence on the housing vibrations, but that this is system-dependent. Since the lateral forces applied to the analyzed hammer drills significantly increased the a_{hv} value, this leads to greater human harm. Hence, design measures should be taken to prevent this.

Funding:

This research was supported in part by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through the financing of the test environment within the context of the proposal GZ: INST 121384/81-1 FUGG. The research results are solely the responsibility of the authors and do not necessarily represent the official views of DFG.

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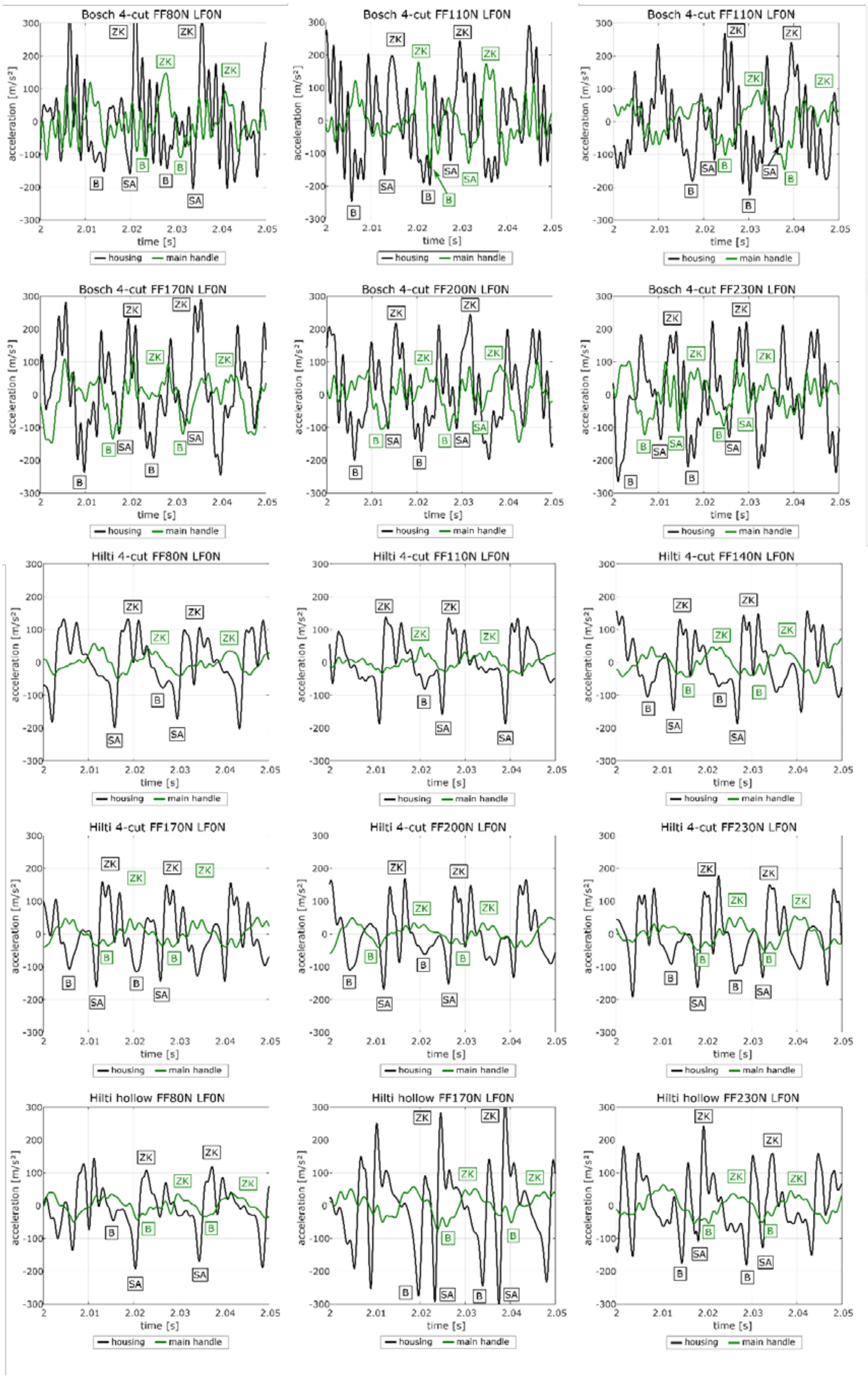

Figure 6. Exemplary influence of feed force on the vibration in x-direction of the housing for both hammer drills

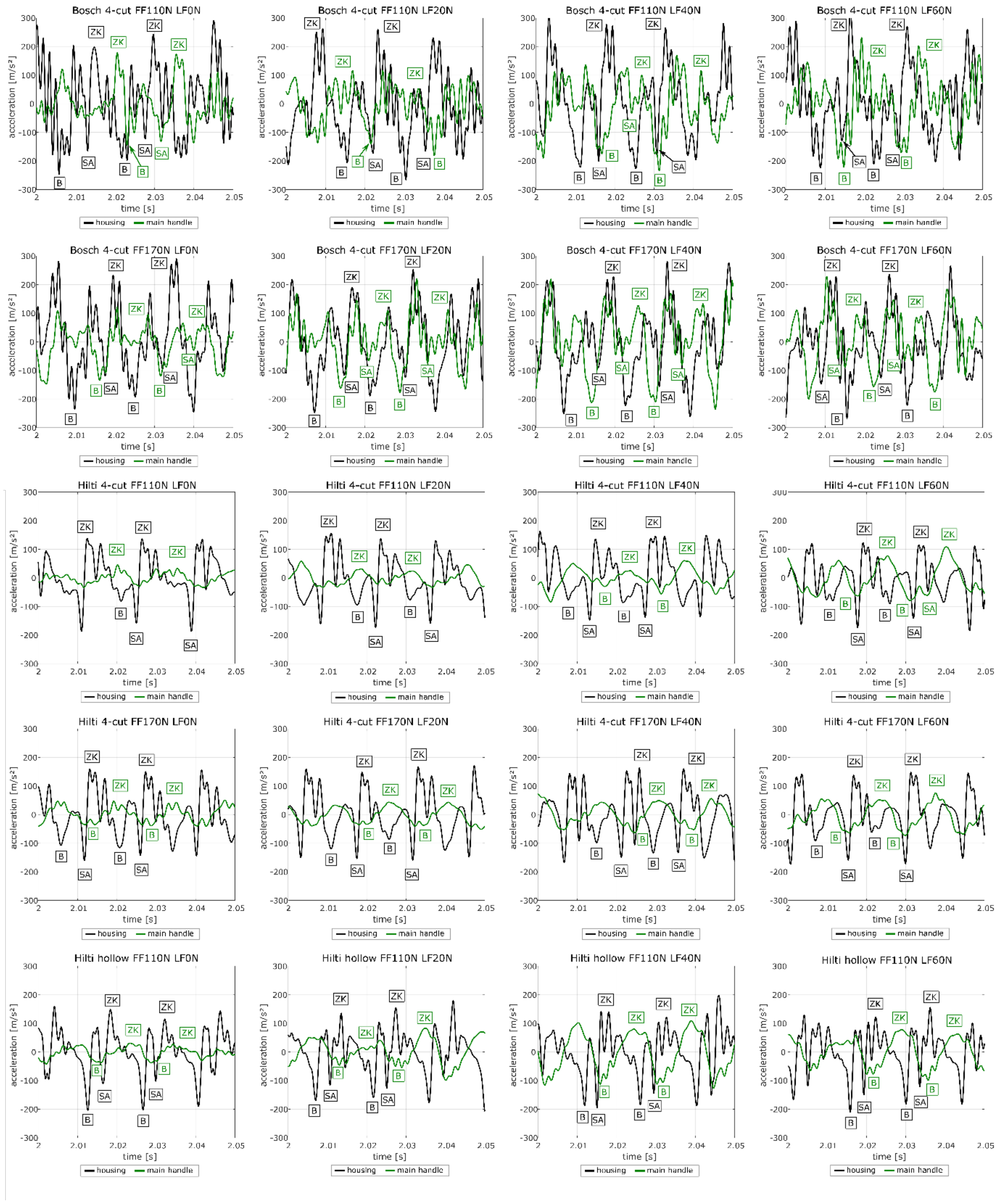

Figure 7. Exemplary influence of lateral force on the vibration in x-direction of the housing for both hammer drills

Table 2. Analysis of the Influence of the feed force on the a_{hv} value at the housing and at the main handle of the TE 30 for each drill bit typ (Ho2c = hollow drill bit, He4c = helical drill bit with 4 cutting edges and He2c = helical drill bit with 2 cutting edges)

Kruskal-Wallis test statistics

	a_{hv} housing									a_{hv} main handle								
	Ho2c (n=192)			He4c (n=192)			He2c (n=192)			Ho2c (n=192)			He4c (n=192)			He2c (n=192)		
	df	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*
	5	39.089	<.001	5	3.014	0.698	5	13.608	.018	5	17.899	.003	5	9.386	.095	5	15.348	.009

Multiple Comparisons

FF [N]	FF [N]	Ho2c housing *z*	*r*	He4c housing *z*	*r*	He2c housing *z*	*r*	Ho2c main handle *z*	*r*	He4c main handle *z*	*r*	He2c main handle *z*	*r*
80	110	**-4.182*** **	0.3	n. s.	n. s.	-1.167	n. s.	**-2.906**$^{\#}$	0.21	n. s.	n. s.	-0.702	n. s.
	140	**-5.216*** **	0.38	n. s.	n. s.	-0.358	n. s.	**-3.484** **	0.25	n. s.	n. s.	-1.298	n. s.
	170	**-5.444*** **	0.39	n. s.	n. s.	-1.568	n. s.	**-3.610** **	0.26	n. s.	n. s.	**-3.302***	0.24
	200	**-4.182*** **	0.3	n. s.	n. s.	-1.667	n. s.	**-3.082***	0.22	n. s.	n. s.	-2.501	n. s.
	230	**-3.507** **	0.25	n. s.	n. s.	-1.233	n. s.	-2.344	n. s.	n. s.	n. s.	-2.346	n. s.
110	140	-0.999	n. s.	n. s.	n. s.	-0.810	n. s.	-0.578	n. s.	n. s.	n. s.	-0.596	n. s.
	170	-1.226	n. s.	n. s.	n. s.	**-2.735**$^{\#}$	0.2	-0.704	n. s.	n. s.	n. s.	-2.600	n. s.
	200	-0.036	n. s.	n. s.	n. s.	**-2.834**$^{\#}$	0.2	-0.175	n. s.	n. s.	n. s.	-1.800	n. s.
	230	-0.711	n. s.	n. s.	n. s.	-2.400	n. s.	-0.562	n. s.	n. s.	n. s.	-1.644	n. s.
140	170	-0.820	n. s.	n. s.	n. s.	-1.926	n. s.	-0.126	n. s.	n. s.	n. s.	-2.004	n. s.
	200	-1.035	n. s.	n. s.	n. s.	-2.024	n. s.	-0.403	n. s.	n. s.	n. s.	-1.203	n. s.
	230	-1.710	n. s.	n. s.	n. s.	-1.590	n. s.	-1.140	n. s.	n. s.	n. s.	-0.295	n. s.
170	200	-1.262	n. s.	n. s.	n. s.	-0.099	n. s.	-0.529	n. s.	n. s.	n. s.	-0.801	n. s.
	230	-1.937	n. s.	n. s.	n. s.	-0.335	n. s.	-1.266	n. s.	n. s.	n. s.	-0.956	n. s.
200	230	-0.675	n. s.	n. s.	n. s.	-0.434	n. s.	-0.738	n. s.	n. s.	n. s.	-0.155	n. s.

Basis: n=1152, Bonferroni-corrected post-hoc test, $^{\#}p<0.1$, $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

Table 3. Analysis of the Influence of the feed force on the a_{hv} value at the housing and at the main handle of the GBH 3-28 for each drill bit typ (Ho2c = hollow drill bit, He4c = helical drill bit with 4 cutting edges and He2c = helical drill bit with 2 cutting edges)

Kruskal-Wallis test statistics

	a_{hv} housing									a_{hv} main handle								
	Ho2c (n=191)			He4c (n=192)			He2c (n=192)			Ho2c (n=191)			He4c (n=192)			He2c (n=192)		
	df	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*
	5	89.771	<.001	5	60.893	<.001	5	48.855	<.001	5	10.741	.057	5	9.126	.104	5	30.106	<.001

Multiple Comparisons

FF [N]	FF [N]	Ho2c housing *z*	*r*	He4c housing *z*	*r*	He2c housing *z*	*r*	Ho2c main handle *z*	*r*	He4c main handle *z*	*r*	He2c main handle *z*	*r*
80	110	-1.558	n. s.	-0.362	n. s.	-0.490	n. s.	n. s.	n. s.	n. s.	n. s.	-2.283	n. s.
	140	-2.702	n. s.	-2.243	n. s.	-2.310	n. s.	n. s.	n. s.	n. s.	n. s.	**-2.765[#]**	0.2
	170	**-3.860****	0.28	**-3.806****	0.27	-2.099	n. s.	n. s.	n. s.	n. s.	n. s.	**-3.606****	0.26
	200	**-6.580*****	0.48	**-5.048*****	0.36	**-4.049*****	0.29	n. s.	n. s.	n. s.	n. s.	-0.947	n. s.
	230	**-7.828*****	0.57	**-6.019*****	0.43	-5.898	n. s.	n. s.	n. s.	n. s.	n. s.	-0.922	n. s.
110	140	-1.153	n. s.	-1.881	n. s.	-1.820	n. s.	n. s.	n. s.	n. s.	n. s.	-0.481	n. s.
	170	-2.320	n. s.	**-3.444****	0.25	-1.608	n. s.	n. s.	n. s.	n. s.	n. s.	-1.323	n. s.
	200	**-5.063*****	0.37	**-4.686*****	0.34	**-3.559****	0.26	n. s.	n. s.	n. s.	n. s.	-1.336	n. s.
	230	**-6.320*****	0.46	**-5.657*****	0.41	**-5.408*****	0.39	n. s.	n. s.	n. s.	n. s.	**-3.205***	0.23
140	170	-1.167	n. s.	-1.563	n. s.	-0.211	n. s.	n. s.	n. s.	n. s.	n. s.	-0.841	n. s.
	200	**-3.910*****	0.28	**-2.805[#]**	0.2	-1.739	n. s.	n. s.	n. s.	n. s.	n. s.	-1.818	n. s.
	230	**-5.167*****	0.37	**-3.777****	0.27	**-3.588****	0.26	n. s.	n. s.	n. s.	n. s.	**-3.687****	0.27
170	200	**-2.743[#]**	0.20	-1.242	n. s.	-1.950	n. s.	n. s.	n. s.	n. s.	n. s.	-2.659	n. s.
	230	**-4.000*****	0.29	-2.213	n. s.	**-3.799****	0.27	n. s.	n. s.	n. s.	n. s.	**-4.528*****	0.33
200	230	-1.257	n. s.	-0.972	n. s.	-1.849	n. s.	n. s.	n. s.	n. s.	n. s.	-1.869	n. s.

Basis: n=1152, Bonferroni-corrected post-hoc test, $^{\#}p<0.1$, $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

Table 4. Analysis of the Influence of the lateral force on the a_{hv} value at the housing and at the main handle of the TE 30 for each drill bit typ (Ho2c = hollow drill bit, He4c = helical drill bit with 4 cutting edges and He2c = helical drill bit with 2 cutting edges)

Kruskal-Wallis test statistics

	a_{hv} housing									a_{hv} main handle								
	Ho2c (n=192)			He4c (n=192)			He2c (n=192)			Ho2c (n=192)			He4c (n=192)			He2c (n=192)		
	df	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*
	3	13.254	.004	3	98.851	<.001	3	1.754	.625	3	138.090	<.001	3	47.485	<.001	3	11.140	.011

Multiple Comparisons

LF [N]	LF [N]	*z*	*r*	*z*	*r*	*z*	*r*	*z*	*r*	*z*	*r*	*z*	*r*
0	20	-3.611**	0.26	-1.098	n. s.	n. s.	n. s.	-4.261***	0.31	-0.279	n. s.	-0.327	n. s.
	40	-1.745	n. s.	-7.291***	0.53	n. s.	n. s.	-9.001***	0.65	-4.044***	0.29	-2.007	n. s.
	60	-2.160	n. s.	-7.765***	0.56	n. s.	n. s.	-10.585***	0.77	-5.690***	0.41	-2.860*	0.21
20	40	-1.866	n. s.	-6.193***	0.45	n. s.	n. s.	-4.740***	0.34	-3.765***	0.27	-1.681	n. s.
	60	-1.415	n. s.	-6.667***	0.48	n. s.	n. s.	-6.324***	0.46	-5.411***	0.39	-2.533	n. s.
40	60	-0.415	n. s.	-0.474	n. s.	n. s.	n. s.	-1.583	n. s.	-1.646	n. s.	-0.852	n. s.

Basis: n=1152, Bonferroni-corrected post-hoc test, #p<0.1, *p<0.05, **p<0.01, ***p<0.001

Table 5. Analysis of the Influence of the lateral force on the a_{hv} value at the housing and at the main handle of the GBH 3-28 for each drill bit typ (Ho2c = hollow drill bit, He4c = helical drill bit with 4 cutting edges and He2c = helical drill bit with 2 cutting edges)

Kruskal-Wallis test statistics

	a_{hv} housing									a_{hv} main handle								
	Ho2c (n=191)			He4c (n=192)			He2c (n=192)			Ho2c (n=191)			He4c (n=192)			He2c (n=192)		
	df	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*
	3	4.783	.188	3	81.999	<.001	3	46.927	<.001	3	122.625	<.001	3	125.069	<.001	3	47.303	<.001

Multiple Comparisons

LF [N]	LF [N]	*z*	*r*	*z*	*r*	*z*	*r*	*z*	*r*	*z*	*r*	*z*	*r*
0	20	n. s.	n. s.	-0.997	n. s.	-0.962	n. s.	-5.927***	0.43	-4.257***	0.31	-4.116***	0.30
	40	n. s.	n. s.	-1.466	n. s.	-2.053	n. s.	-9.477***	0.69	-10.109***	0.73	-5.328***	0.38
	60	n. s.	n. s.	-7.268***	0.52	-5.359***	0.39	-9.701***	0.7	-8.621***	0.62	-6.425***	0.46
20	40	n. s.	n. s.	-2.463#	0.18	-3.016*	0.22	-3.569**	0.26	-5.852***	0.42	-2.309	n. s.
	60	n. s.	n. s.	-8.265***	0.6	-6.322***	0.46	-3.794***	0.27	-4.364***	0.31	-1.212	n. s.
40	60	n. s.	n. s.	-5.802***	0.42	-3.306***	0.24	-0.225	n. s.	-1.488	n. s.	-1.096	n. s.

Basis: n=1152, Bonferroni-corrected post-hoc test, #p<0.1, *p<0.05, **p<0.01, ***p<0.001

KIT Scientific Working Papers
ISSN 2194-1629
www.kit.edu