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Effect of Bit Wear on Hammer Drill Handle Vibration and Productivity

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ABSTRACT

Introduction: The use of large electric hammer drills exposes construction workers to high levels of hand vibration that may lead to hand arm vibration syndrome and other musculoskeletal disorders. The aim of this laboratory study was to investigate the effect of bit wear on drill handle vibration and drilling productivity (e.g., drilling time per hole).

Methods: A laboratory test bench system was used with an 8.3 kg electric hammer drill and 1.9 cm concrete bit (a typical drill and bit used in commercial construction). The system automatically advanced the active drill into aged concrete block under feed force control to a depth of 7.6 cm while handle vibration was measured according to ISO standards (ISO 5349 and 28927). Bits were worn to 4 levels by consecutive hole drilling to 4 cumulative drilling depths: 0, 1900, 5700 and 7600 cm.

Results: Z-axis handle vibration increased significantly (p<0.05) from 4.8 to 5.1 m/s^2 (ISO weighted) and from 42.7 to 47.6 m/s^2 (unweighted) when comparing a new bit to a bit worn to 1900 cm of cumulative drilling depth. Handle vibration did not increase further with bits worn more than 1900 cm of cumulative drilling depth. Neither x- nor y- axis handle vibration was
effected by bit wear. The time to drill a hole increased by 58% for the bit with 5700 cm of cumulative drilling depth compared to a new bit.

**Conclusion:** Bit wear led to a small but significant increase in both ISO weighted and unweighted z-axis handle vibration. Perhaps more important, bit wear had a large effect on productivity. The effect on productivity will influence a worker’s allowable daily drilling time if exposure to drill handle vibration is near the ACGIH Threshold Limit Value (1). Construction contractors should implement a bit replacement program based on these findings.

**KEYWORDS**

hand arm vibration syndrome, tool vibration, tool design, concrete drilling, musculoskeletal disorders.
INTRODUCTION

Electric hammer drills are widely used in commercial construction for drilling into concrete for structural upgrades and anchor bolt placement. Pneumatic rock drills, the primary tool used for dowel and rod work, have been gradually replaced by new, more powerful electric hammer drills. Although electric hammer drills may expose workers to less hand-vibration and noise compared to pneumatic drills the exposure to these hazards still remains high. (2) Hand vibration exposure may lead to hand-arm vibration syndrome, which can cause disorders of the blood vessels, nerves, bones, joints, muscles or connective tissues of the hand and forearm. (3-6)

Incorporation of anti-vibration and ergonomic concepts into the design of tools and tasks in the last two decades have contributed to the reduction in industrial exposures to hand-arm vibration syndrome. Nevertheless, hand-arm vibration syndrome remains an important problem among construction workers and miners who use cement cutting tools, such as rock and hammer drills. (7)

The average handle vibration levels of electric hammer drills (8) are higher than the threshold limit value recommended by the ACGIH (1) and the European Community Directive. (9) Typical handle vibration levels for hammer or rock drills vary from 6 to 20 m/s². (10) Accurate exposure data is essential because of relationship between vibration level and the threshold limit value maximum exposure time is exponential.

The use of personal protection equipment (PPE) such as anti-vibration gloves only partially reduces vibration exposure, since the frequencies filtered out by the gloves are higher than 315/400 Hz. (11,12) Furthermore, anti-vibration gloves may introduce adverse effects such as increased grip force and reduced manual dexterity. (13)
The vibration levels reported by manufacturers for hammer drills may over- or under-estimate real workplace risk depending on the specific conditions of data collection. (14-16) Manufacturers typically report a single handle vibration value using a standard condition. However, many factors may impact drill handle vibration levels. For example, several studies of hammer drills, that were conducted according to ISO 5349-1(17), have identified a positive correlation between bit diameter and handle vibration magnitude.(15, 18) Hammer drill design and operator technique can also influence handle vibration level.(19) Differences in applied grip force among experienced operators using the same tool can contribute to variation in vibration transmission by 50% or more, indicating that the measurement of grip force is essential for modeling vibration transmission and vibration exposures.(20) Furthermore, vibration frequency resulting from drill speed can influence grip force and, therefore, vibration exposure via reflex mechanisms.(21) These considerations are important since the ISO 28927-10 (22) method for vibration measurement on drills prescribes measurement with real use of the drills by experienced workers introducing variance due to differences in operator techniques.

While studies have investigated the relationship of bit sharpness (e.g., wear) to cutting productivity (23-25), the relationship between different levels of bit wear and drill handle vibration has not been evaluated. Some studies have investigated changes in vibration frequency produced from different aged bits used in vertical milling machines in order to predict machine or part damage and minimize scrap and rework. (26, 27). These studies found that the vibration frequency band increased with increased bit wear at the very high frequency range (>1000 Hz), which is beyond the range considered in the ISO standards. Furthermore, these studies did not use concrete cutting bits.
The purpose of this laboratory study was to use an automated test bench system to evaluate the effect of concrete bit sharpness on hammer drill handle vibration levels and productivity (e.g., bit penetration rate). This approach improves reliability and reduces variability of measures compared to measurements collected while experienced workers perform drilling. The null hypothesis was that bit sharpness does not change handle vibration levels or productivity. Vibration measurement methods generally followed ISO 28927-10.(22)

**METHODS**

This laboratory study was conducted using a new test bench system for hammer drills, previously described and validated, but updated to improve accuracy and reliability. The test bench system was previously validated by handle vibration levels on the test bench system to handle vibration while 4 experienced construction workers manually drilled into cement blocks following ISO methods.(28)

A hammer drill is secured to a 6-axis load cell by a force adjustable grip placed at the drill handle location where a hand would hold the drill. The drill is supported near the chuck with a vertical Y support. Linear actuators automatically and repeatedly position the drill and drive the active drill into a concrete block under closed-loop feed force control (i.e., weight-on-bit force). The measured outcomes during drilling are productivity and handle vibration. The system is designed according to the EU, ISO, and German BG BAU IFA guidelines for a test bench system (EN 1093-3:2006; CEN: CMT4-CT97-2166; BG BAU 617.0-FF 421 2006).

A sketch, diagram and dynamic model of the drill assembly are presented in Figure 1. The hammer drill (Hilti TE-70; 8.3 kg; 46 Hz percussion frequency) (a), is secured to a 6-axis load cell (9105-TIF-THETA-IP65, ATI, Apex, NC) (f) by a four fingered rubber-lined
mechanical gripper (c). The rubber is 6.35 mm thick Neoprene (Product 1294N175; ASTM D2000 BC, McMaster-Carr) with stiffness properties similar to palmar skin.(29) The grip force is adjusted using a torque driver (J6169F, Proto, Conyers, GA); the torque measure is calibrated to grip force using a hand dynamometer (JAMAR 2A, Lafayette Instrument, Lafayette, IN).

The load cell is height adjustable on a tower (b) to accommodate different size drills. The linear actuator (g) advances the carriage (e) that supports the drill. Between the actuator and drill there is a sliding spring assembly (d) that approximates the mechanical impedance of the upper extremity during drilling. In the Mass-Spring Biodynamic Model (30, 31), m1 represents the mass of the tower (b) and mounting plate (d); c1 represents a friction damper between d and e; and k1 is the pair of springs at d. The mass of the rubber and hose clamps is m2; with the rubber acting as both spring and damper (c2, k2).

The drill assembly is part of a larger system that automatically advances concrete blocks horizontally after each hole is drilled (Figure 2). The drill is turned on, and pushed horizontally by a linear actuator. When the turning bit contacts the block the feed force, controlled with the 6-axis load cell, drives the advancement of the drill to maintain a constant feed force. When a predetermined hole depth is reached (7.6 cm in this study) the drill is withdrawn, the concrete block clamp linear actuator is released and the blocks are advanced with a third linear actuator. Six evenly spaced holes are drilled per block. All actuators are controlled by a custom LabView software on a PC.

Non-reinforced concrete blocks (10 × 15.25 × 58.4 cm) were prepared on site according to EN and ISO standards (slump 80 mm; EN 206-1:2000; ISO 679; ISO 28927-10) and cured for at least 28 days.
Tool handle vibration acceleration magnitude was measured and interpreted according to ISO 28927 with two differences facilitating drill operation and improving measure reliability. Drilling was done horizontally to avoid bit binding which can occur when drilling vertically as prescribed by the ISO standard. The human operator was replaced by an automated system simulating a stable dynamic behavior.

Drill handle vibration was measured with a tri-axial piezoelectric accelerometer (Larson Davis SEN040F; sensitivity of 1mv/g) attached to the drill handle at the location of hand grip using a hose clamp and oriented according to ISO 5349-2 (z-axis aligned with drill bit axis; x-axis vertical). Only one axis was measured for each hole drilled due to the limitations of the data logger (Svantek 912AE). The accelerometer was calibrated at the beginning and at the end of each test by a PCB Piezotronics 394C06 calibrator. The signals were analyzed by Svantek software (SVANPC V2.3w) to generate the 1/3 octave spectra as well as the unweighted \((a_h)\) and weighted \((a_{h,w})\) acceleration levels for each axis and total value according to ISO 5349-1. Tool handle vibration acceleration magnitudes are interpreted according to ISO 28927-10. Both ISO weighted and unweighted spectra of the vibration are reported as the scientific community is not in complete agreement with the best predictors of hand-arm vibration disorder risk.\(^{(32-34)}\) The ISO frequency weighting function reduces the contribution of higher frequencies for risk estimation.

Four levels of bit wear were produced by repeatedly drilling holes of 19 cm in depth into concrete block (Figure 3). The four levels correspond to cumulative drilling depths (CDD) of 0, 1900, 5700, and 7600 cm. All bits were 34.3 cm long, 1.9 cm in diameter, 2-cutter carbide (DeWalt DW5872). The drill and bits used in the study are typical of the tools used in the trades.
Handle vibration and drilling rate experimental data were collected for each of the 4 bit wear levels on the test bench during the drilling of 18 holes; 6 holes for each axis of acceleration measurement. Hole depth during the experiment was 7.6 cm and the target feed force was 150 N. Productivity was estimated for each cumulative drilling depth level by averaging the drilling time per hole over the 18 holes drilled. Differences in acceleration and productivity were evaluated statistically using one-way ANOVA with Tukey follow-up test to correct for multiple comparisons. Significant differences, if present, were also evaluated with effect size calculations (Cohen’s d). Effect size emphasizes the size of the difference rather than confounding this with sample size.

RESULTS

Drilling rate was significantly influenced by bit wear (Table I and Figure 4) (p = 0.00001). The mean drilling time per 7.6 cm hole increased from 7.8 s for a new bit, to 10.3 s for a bit with 1900 cm of cumulative drilling depth, to 12.3 s for a bit with 5700 cm of cumulative drilling depth, but did not increase further for the bit with 7600 cm of cumulative drilling depth. The effect size (Cohen’s d) for a new bit compared to the 1900 cm worn bit was 5.49 [95% CI: 5.35-5.63] and for the new bit compared to the 5700 cm worn bit was 11.79 [95% CI: 11.67-11.91]. The reduction in productivity was relatively linear from a new bit up to the 5700 cm of cumulative drilling depth bit.

The spectra of unweighted and weighted handle total acceleration (combined x-y-z axes), across the range of bit wear conditions, are presented in the Figures 5 and 6. The unweighted spectra exhibit a major peak between 200 and 630 Hz and a secondary peak at 50 Hz corresponding to the drill percussion frequency (Figure 5). The weighted spectra exhibit a major
peak at 50 Hz and a secondary peak between 100 and 315 Hz (Figure 6). For the unweighted spectra, the acceleration level for a new bit was lowest at 315 Hz compared to the worn bits, while for the weighted spectra the acceleration level for a new bit was lowest at 50 Hz compared to the worn bits.

There was little effect of bit wear on unweighted x-axis, y-axis, and combined (total) acceleration ($a_h$) levels (Table I). However, the unweighted z-axis acceleration level was significantly lower for the new bit than any of the worn bits based on the overall ANOVA ($p = 0.00001$) and Tukey follow-up tests. A similar pattern was observed for weighted acceleration ($a_{hw}$) with significant effects only along the z-axis ($p = 0.003$). Again, acceleration levels for the new bit were less than any of the bits with wear.

The effect sizes (Cohen’s d) for the unweighted z-axis acceleration levels for a new bit compared to the 1900, 5700 and 7600 cm worn bits were 3.23 [95% CI: 2.38-4.07], 2.68 [95% CI: 2.07-3.28], and 2.26 [95% CI: 1.67-2.84], respectively. The effect sizes for the weighted z-axis acceleration levels for a new bit compared to the 1900, 5700 and 7600 cm worn bits were 2.63 [95% CI: 2.56-2.69], 2.45 [95% CI: 2.39-2.50], and 1.60 [95% CI: 1.52-1.68], respectively.

**DISCUSSION**

This novel laboratory study used an updated test bench system to systematically evaluate the effects of bit wear on hammer drill handle vibration. To some extent, both frequency weighted ($a_{hw}$) and unweighted ($a_h$) handle vibration levels were influenced by bit sharpness. The effects were significant only in the z-axis, which is the axis collinear to the forearm. The unweighted z-axis vibration level increased 11.3%, from 42.7 m/s$^2$ with a new bit to 47.5 m/s$^2$ with a 1900 cm cumulative drilling depth bit (Figure 7). These corresponded to large effect sizes,
with Cohen’s d values above 2. The increase in z-axis vibration level was less conspicuous for weighted acceleration, which heavily discounts the high frequencies (Figure 8); however, the effect sizes were still large, with Cohen’s d values above 1.6. Since the weighting function modifies the profile of the vibration spectrum, the effects of bit wear are most evident for 200-630 Hz for unweighted measures and 50-200 Hz for the weighted measures, which correspond to the hammering frequency and the subharmonic of this frequency. These results indicate that bit wear contributes to a significant increase in high frequency vibration, which may be too heavily discounted by the current ISO weighting function.(32, 34) Indeed, high frequency handle vibration can increase grip force and exacerbate muscle fatigue, both of which may contribute to vibration exposure and disease.(21,35,36)

Z-axis handle vibration is proportional to the energy reflected back from the drill bit impacting concrete. The percussive system of the hammer drill tested operates at a frequency of 46 Hz so that the tip penetrates the concrete under compressive stress leading to tensile cracks and the formation of pulverized concrete. After each strike, the bit tip rotates slightly splitting the concrete and the bit blades move to a new strike area. Some of the energy from the impactor is imparted to crush concrete and some of the energy is reflected back to the tool handle. As the bit becomes dull, less energy from each impact is transferred to splitting the concrete and instead is reflected back up the bit.

Other laboratories have developed automated laboratory drilling platforms for investigating bit characteristics and penetration rates but they have not evaluated tool vibration levels.(37,38) These laboratories have studied impregnated diamond bits used for rock drilling
and have generated models for diamond and matrix wear and penetration rate but they have not evaluated wear on concrete bits and penetration rate. (39)

An important factor to consider when estimating exposure to drill handle vibration is that the drilling time per hole is less with a new bit, thereby reducing the duration of exposure to hand vibration, when compared to a worn bit. A moderately worn bit (1900 cm CDD) increases drilling time by 32% while a very worn bit (5700 cm CDD) increases drilling time by 58%. There was no significant difference in drilling time between the bit with 5700 cm of cumulative drilling depth and the bit with 7600 cm of cumulative drilling depth indicating that for this particular bit wear progressed up to somewhere between 1900 and 5700 cm of cumulative drilling depth bit wear but beyond that point there is little further effective wear.

Bit wear will affect the number of holes a worker can drill per day due to the time spent drilling if the exposure is near the threshold limit value (ACGIH TLV for Hand Arm Vibration, 2016). At a handle vibration level of 8 m/s$^2$ $a_{h,w}$ the threshold limit value is 187 minutes of vibration exposure per day. If it takes 2 minutes to drill a hole with a sharp bit, at most, a worker could drill 93 holes per day. With a very worn bit, it would take 3.2 minutes to drill the same hole, and, at most, a worker could drill 58 holes per day.

These differences should provide a financial and safety incentive for construction contractors to adopt a bit replacement program. Not only does a sharp bit reduce drilling time per hole and worker fatigue, but more holes can be drilled per day. The return-on-investment calculations will depend on many factors, such as cost of bits, hourly wage, number of holes drilled per day and depth of hole. A bit replacement program could be based on measurable changes in bit geometry or on the cumulative drilling depth history for a bit.
Several limitations of this study should be noted. First, the feed force applied during drilling was less for the new bit (145 N) than the bits with wear (148 -- 150 N) (Table I). These differences are likely due to the rapid cutting speed with a sharp bit and the relative response lag in the force control system compared to the cutting speed with worn bits. These differences in feed force were small and do not explain the observed differences in drilling time or handle vibration levels. Second, only one hammer drill and bit type were studied. Other drills and bits should be evaluated to determine if the effects of bit wear on handle vibration and productivity are reproduced. Finally, the test bench system differs from the ISO standard, which calls for handle vibration to be measured while the tool is operated by expert workers. The ISO method accommodates sampling across the differences in worker grip force and worker applied feed force. The test bench produces much more reliable results, and can, therefore, better detect differences between drills, bits and applied force on handle vibration. On the other hand, while bench results are more reliable, the results may not represent all the possible ways a worker will use a drill. These findings should be confirmed with human studies.

CONCLUSIONS AND RECOMMENDATIONS

This hammer drill laboratory study showed a small but significant increase in z-axis handle vibration and exposure time with worn concrete bits when compared to a new bit. Drill bit manufacturers may consider advising contractors that worn bits will increase the exposure of workers to hand vibration and will reduce worker productivity. Construction contractors should consider adopting bit replacement programs based on bit wear patterns or cumulative bit usage.

DISCLOSURES

The findings and conclusions in this report are those of the authors and do not necessarily
represent the official position of the NIOSH or CPWR. Mention of product names does not imply endorsement. The authors identify no conflicts of interest in the conduct of this study.

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REFERENCES

1. ACGIH: 2016 TLVs and BEIs: Threshold Limit Values, ACGIH, Cincinnati, OH (2016).


TABLE I. Mean (SD) drilling time per hole (7.6 cm depth holes), feed force, and unweighted and weighted handle vibration levels by bit wear level in cumulative depth drilled.

<table>
<thead>
<tr>
<th>Bit Wear (cumulative drilling depth)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>p-value</th>
<th>F-value$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm</td>
<td>1900 cm</td>
<td>5700 cm</td>
<td>7600 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drilling time (s)</td>
<td>7.8 (0.4)$^{abc}$</td>
<td>10.3 (0.7)$^{abc}$</td>
<td>12.3 (0.6)$^{cd}$</td>
<td>11.8 (0.7)$^{de}$</td>
<td>0.00001</td>
<td>190.4</td>
</tr>
<tr>
<td>Feed force (N)</td>
<td>145 (4)$^{abc}$</td>
<td>148 (3)$^b$</td>
<td>150 (1)$^b$</td>
<td>149 (3)$^b$</td>
<td>0.00001</td>
<td>10.4</td>
</tr>
</tbody>
</table>

Unweighted (a_h)

| X-Axis (m/s²)                      | 67.7 (2.4) | 65.2 (4.9) | 68.4 (3.8)$^a$ | 61.6 (2.8)$^a$ | 0.03   | 3.6        |
| Y-Axis (m/s²)                      | 45.4 (2.3) | 47.3 (1.1) | 44.1 (1.7) | 45.5 (2.0) | 0.10   | 2.4        |
| Z-Axis (m/s²)                      | 42.7 (1.3)$^{abc}$ | 47.6 (1.6)$^{cd}$ | 45.6 (0.7)$^b$ | 45.1 (0.6)$^{cd}$ | 0.00001 | 14.8       |
| Total (m/s²)                       | 92.1 (2.1) | 93.6 (3.3) | 93.3 (3.5) | 88.9 (2.6) | 0.07   | 2.7        |

Weighted (a_hw)

| X-Axis (m/s²)                      | 5.5 (0.2) | 5.4 (0.3) | 5.7 (0.3) | 5.3 (0.1) | 0.08   | 2.6        |
| Y-Axis (m/s²)                      | 2.7 (0.2) | 2.9 (0.2) | 2.6 (0.1) | 2.8 (0.1) | 0.05   | 3.1        |
| Z-Axis (m/s²)                      | 4.8 (0.1)$^{abc}$ | 5.1 (0.1)$^a$ | 5.0 (0.1)$^b$ | 5.0 (0.2)$^a$ | 0.003  | 6.4        |
| Total (m/s²)                       | 7.8 (0.2) | 8.0 (0.3) | 8.0 (0.2) | 7.8 (0.1) | 0.14   | 2.0        |

Notes: The same superscripts in a row indicate significantly different values by the Tukey test.

$^2$Between df were 3 for all tests. Within df were 68 for drilling time and feed force and 20 for the vibration levels.
FIGURE 1. Sketch, diagram and dynamic model of the drill assembly with elements of the system identified.
FIGURE 2. Test bench system with hammer drill secured to 6-axis load cell with grips on the handle; this assembly is pushed on a lathe bed by the linear actuator under the mannequin. The concrete blocks are secured with a linear actuator during drilling and are advanced automatically with a different linear actuator (not in figure). A mannequin is in place to simulate the location of the worker.
FIGURE 3. The four levels of bit wear were (A) new bit, (B) 1900 cm, (C) 5700 cm, and (D) 7600 cm of cumulative depth drilled.
FIGURE 4. Mean (95% CI) drilling time per 7.6 cm hole by bit wear.
FIGURE 5. Unweighted frequency spectra of RMS sum (x-y-z) vibration level by bit wear
FIGURE 6. Weighted frequency spectra of RMS sum (x-y-z) vibration level by bit wear
FIGURE 7. Mean (95%CI) unweighted acceleration per bit wear cumulative depth drilled level.
FIGURE 8. Mean (95% CI) weighted acceleration per bit wear cumulative depth drilled level.