International Journal of Industrial Ergonomics 80 (2020) 103049

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: http://www.elsevier.com/locate/ergon

R2: Drilling into concrete: Effect of feed force on handle vibration and productivity

Lucia Botti [a], Bernard Martin [b], Alan Barr [b], Jay Kapellusch [b], Cristina Mora [a], David Rempel [b,*]

[a] Department of Industrial Engineering, University of Bologna, Italy

[b] Department of Bioengineering, University of California, Berkeley, CA, USA

ARTICLE INFO

Keywords:
Hand-arm-vibration syndrome
Tool design
Occupational health
Vibration

ABSTRACT

Approximately 1.6 million commercial construction workers in the US use rotary hammer drills for drilling into concrete to insert anchor bolts or rebar. The exposure to vibration may lead to hand-arm vibration syndrome and other musculoskeletal disorders depending on handle vibration acceleration level, hand grip force, and duration of exposure. There is little information on the relationship between feed force (FF), e.g., the push force applied by the worker, and handle vibration. A robotic test bench for rotary hammer drills was used to evaluate the effects of different FF on handle vibration and productivity (e.g., penetration rate and holes drilled). Increasing FF from 95 to 163 N was associated with an increase in total weighted handle vibration (a_{hv}) of 7.2–8.5 m/s^2 (slope, $p < 0.001$) but from 163 to 211 N there was no change in vibration level (slope, $p = 0.17$). Increasing FF from 95 to 185 N was associated with an increase in penetration rate of 7.2–8.5 m/s^2 (slope, $p < 0.001$) but from 185 to 211 N there was no change in penetration rate (slope, $p = 0.49$). Based on the maximum allowable duration of exposure to hand vibration, specified by the ISO and ACGIH Action Limits, and the penetration rate, the drilling productivity, in m drilled per day, is greatest for the lowest FF tested. Contractors and construction workers should be informed that when drilling into concrete, the lowest exposure to harmful hand vibration and the best overall productivity occurs when the lowest operational FF is applied during hammer drilling.

1. Introduction

Commercial construction workers use rotary hammer drills to drill into concrete for placing anchor bolts in order to hang pipes or conduit or for setting rebar (e.g., dowel and rod) for structural retrofits. In 2019, the construction trades in the US that drill into concrete were cement masons (196,120), laborers in foundation, utilities and structural industries (241,360), carpenters in foundation and structural industries (99,660), electricians (688,620) and plumbers (442,870), for a total of 1,668,630 workers (U.S. BLS, 2019). In a study of powered construction tools, rotary hammer drills had the highest mean weighted handle vibration (15 m/s^2) followed by sabre saws (11 m/s^2), screw drivers (5 m/s^2) and grinders (3 m/s^2) (Vergera et al., 2008).

Exposure to hand vibration during rock or concrete hammer drilling can cause upper extremity musculoskeletal disorders, such as hand-arm vibration syndrome (Bovenzi, 1994; HSE, 2005; Poole et al., 2019). The probability of developing hand-arm vibration syndrome is related to the exposure dose which is dependent on several factors including handle vibration magnitude, grip force, duration of daily exposure, and years of exposure (Welcome et al., 2014). International and national standards have been established to limit the number of hours of exposure to a vibrating hand tool based on the tool handle vibration level (ISO 5349, 2001; ACGIH, 2020). For example, for a tool with a handle vibration level of 21 m/s^2, the maximum allow total exposure time in a day would be 7 min (ISO 5349, 2001).

In addition, if the hands are tightly coupled to the tool, e.g., with a high grip or push force, then more vibration energy is transmitted to the hands and arms thereby increasing the probability of tissue damage (McDowell et al., 2007; Dong et al., 2005, 2010; Deshmukh and Patil, 2012; Welcome et al., 2015; Xu et al., 2015; Pan et al., 2018). The hand forces applied to a drill are influenced by the weight of the drill, drill stability requirements, and the feed force necessary to perform the hammer drilling task. Workers may apply greater feed force (FF); e.g., push force or force-on-bit, than necessary when drilling because the force exerted on a tool is underestimated when it is vibrating (Park and Martin, 1993; Martin and Park, 1997). Furthermore, workers may assume that they are being more productive, e.g., the hole is drilled faster, when they apply a greater FF.

* Corresponding author. University of California, Berkeley, Ergonomics Program, 1301 S. 46th Street, Building 163, Richmond, CA, 94804, USA.
E-mail address: david.rempel@ucsf.edu (D. Rempel).

https://doi.org/10.1016/j.ergon.2020.103049
Received 27 December 2019; Received in revised form 28 August 2020; Accepted 8 October 2020
Available online 15 October 2020

There is evidence that a higher FF will increase hammer drilling penetration rate, e.g., productivity, when using a rotary hammer drill (Uhl et al., 2019). However, the relationships between FF and drill handle vibration and productivity, and the tradeoff between the two, has not been well characterized.

This study used an automated test bench system for rotary hammer drills to evaluate the effects of FF on handle vibration magnitude and penetration rate while repeatedly drilling into standardized, cured concrete. Daily productivity was also estimated based on handle vibration levels associated with different FFs and the health standards that set a maximum duration of exposure per day permitted for a given level of handle vibration.

2. Methods

A validated, automated test bench system for rotary hammer drills (Rempel et al., 2017; Antonucci et al., 2017) automatically advances an active drill into a concrete block under force control while drill handle vibration and penetration rate are measured (Fig. 1).

2.1. Equipment setup and control system

The drill is gripped at the handle with a 4-finger rubber lined gripper that mimics finger stiffness, the gripper is secured to a 6-axis load cell (9105-TIF-THETA-IP65, ATI, Apex, NC, USA), and the drill is supported near the chuck with a vertical Y support. The drill and load cell are mounted on a plate that is coupled to a linear actuator with a mass and spring system to mimic hand/arm biodynamics (Rempel et al., 2017). The linear actuator moves the assembly along a lathe bed toward a concrete block and, after contact of the bit tip to the block, advances the rotating bit into the block under programmed force control. After the programmed hole depth is reached, the drill is retracted, the vacuum hose is moved away from the block, the block clamp is released, the block is advanced, the block clamp is tightened on the block, the vacuum hose is moved back into position, and the next hole is drilled. Six holes are drilled into each block. The full, automated cycle for 1 hole takes approximately 1 min.

The load cell measures FF which is monitored by custom closed-loop feed force control program (Labview™, National Instruments, Austin, TX, USA) on a PC at 300 Hz that controls the linear actuator that moves the drill assembly. The system also controls linear actuators that moves the vacuum hose, unclamps and clamps the concrete block and advances the blocks.

Non-reinforced concrete blocks (10 × 15 × 58 cm) were prepared according to ISO standards (ISO 28927–10) and cured for at least 28 days.

2.2. Vibration and drilling productivity measurement

A tri-axial accelerometer (SV106, Svantek, Poland) was attached to the drill handle with a hose clamp (Fig. 1) with the z-axis aligned with drill bit axis and the y-axis aligned to vertical (ISO 28927-10 (2011)). Signal sampling frequency was 6 kHz and the unweighted (a_h) and weighted (a_{hw}) acceleration values for each axis and the vector sum according to ISO 5349–1 were stored on a computer at a frequency of 2 Hz (Svan PC++ v.2.5.18, Svantek, Poland). The accelerometer was calibrated at the beginning and end of data collection (394C06 shaker, PCB Piezotronics, NY, USA).

Drilling productivity per hole, recorded as penetration rate (mm/s), was calculated from the load cell recorded data as the time it took to drill the hole to the programmed depth.

2.3. Experimental parameters

A total of 56 holes of 76 mm depth and 19 mm diameter were drilled into concrete blocks with a 10 kg electric rotary hammer drill (TE 70-ATC, Hilti, Liechtenstein). The bit was replaced with a new bit after every 8 holes drilled. The replacement frequency was based on a prior

Fig. 1. Experimental setup. Drill handle is attached to 6-axis load cell with finger-like clamps. The platform supporting the drill and load cell slides on a lathe bed and is advanced by a linear actuator. A hose clamp on the handle secures the accelerometer to the handle. During drilling, the drill bit moves through a vacuum attachment into a block.

study showing little difference in handle vibration or penetration rate when hammer drilling with a new bit at a FF of 200 N across 6 holes (Botti et al., 2017). A random selection of FF was programmed into the system, but the actual measured mean FF applied for each hole, which ranged from 94.7 to 211 N, was used for data analysis. The actual mean feed force differed from the programmed force due to differences on the initial interaction of the bit with the concrete and the composition of the concrete in the region drilled. The programmed feed force was, on average, 4.5 N higher (SD = 10.8) than the actual feed force. In prior studies, push force during manual concrete hammer drilling ranged from 70 to 180 N (Rempel et al., 2017; Uhl et al., 2019).

2.4. Statistical methods

The three outcome measures, e.g., unweighted and weighted vector sum vibration levels and penetration rate, were plotted against actual mean FF of each hole. The corresponding graph indicated that the vibration magnitudes and penetration rate appeared to increase linearly up to an inflection point and then level off. Smooth (loess) plots of null model residual values from the three models revealed linear increases followed by linear decreases with precise inflection points between the two lines. Linear spline regression (Muggeo, 2003) was used to automatically determine the inflection point (i.e., knot) and to quantify the slopes of each model's two linear splines. Statistical analyses were performed in R, version 3.6.3 (R Core Team, 2020). Spline regression models were analyzed using the 'segmented' package, version 1.1–0 (Muggeo, 2008). Shapiro-Wilk test was used to determine if residual values were normally distributed with $p > 0.05$. Regression results were considered statistically significant at $p \leq 0.01$.

2.5. Application of exposure limits to estimate daily productivity

The ISO 5349 standard (2001) and the ACGIH Hand-Arm Vibration TLV (2020) specify limits to daily exposure time as a function of the weighted vector sum hand-arm vibration level (a_{hv}, m/s^2). The Action Limit prescribes the maximum recommended daily allowable exposure that is a total 8-h energy equivalent of 2.5 m/s^2 ($a_{hv(AL)}$ = 2.5 m/s^2 for 8 h). Exposures above the Action Limit require actions to control exposure, including training workers and supervisors on early symptoms of HAVS, a medical surveillance program and other interventions. The time duration in minutes to reach the Action Limit is defined by the following equation:

Time Duration (min) T_v to reach Action Limit = $60*50/a^2_{hv}$

The acceleration values observed in the study were compared to the Action Limit to determine the safe daily exposure duration of drill use. These were combined with the penetration rate to determine overall daily productivity as a function of the FF.

3. Results

3.1. Force and vibration measurements

Both the unweighted (Fig. 2) and weighted (Fig. 3) handle vibration acceleration values, along the x, y and z axes and their vector sum, appeared to gradually increase with increasing FF from approximately 90 to 160 N. Beyond a FF of 160 N there was little change in vibration vector sum acceleration levels. A similar pattern was observed for the vibration levels along each axis. A similar pattern was also observed for the penetration rate (Fig. 4). Increasing FF from approximately 90 to 180 N was associated with increasing penetration rate, but above 180 N there was little change in penetration rate.

A simple linear regression model was fit to the vector sum unweighted and weighted acceleration data and to the penetration rate data - the parameters and R^2 values for the models are presented in Table 1. All three data sets were also fit with two linear splines with the inflection point, or knot, set to optimize R^2. The parameters for the linear splines, their R^2 values, and a statistical comparison to a line of zero slope are presented in Table 1. The optimized inflection points, or knots, for the vector sum unweighted acceleration, vector sum weighted acceleration and penetration rate were 160.4, 163.4, and 184.7 N, respectively. The linear spline fit for the weighted vector sum acceleration improved the R^2 from 0.28 to 0.42. Repeating the analyses after removing the outlier point at 211 N did not change the direction or significance of any of the findings.

3.2. Maximum allowable exposure time and resultant daily productivity

The relationships of penetration rate, allowed minutes of exposure per day per ISO 5349, and daily productivity as a function of FF are presented in Fig. 5. The estimated penetration rate and the weighted

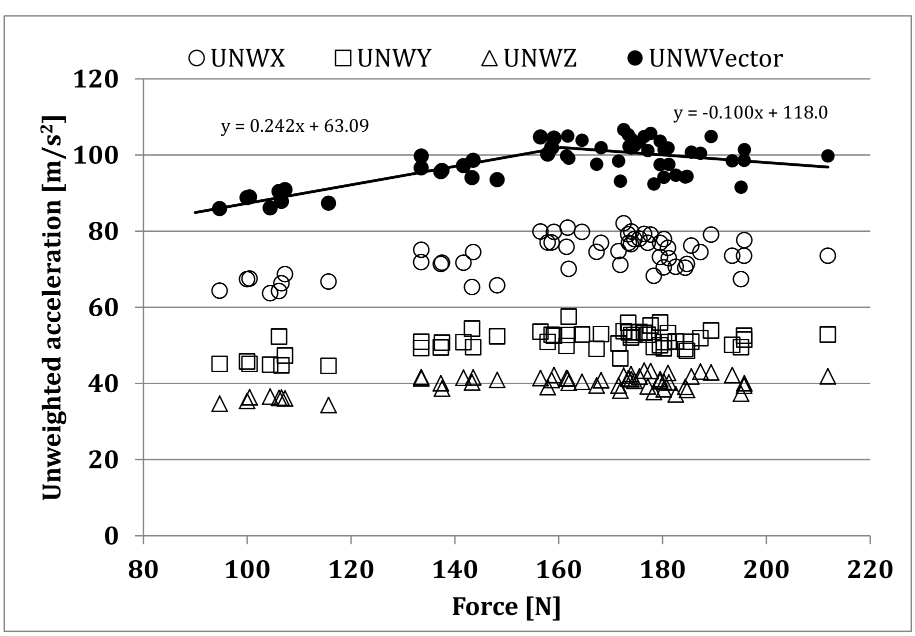

Fig. 2. Unweighted individual axes and vector sum acceleration by feed force for each hole drilled. The inflection point for the vector sum data is at 160.4 N.

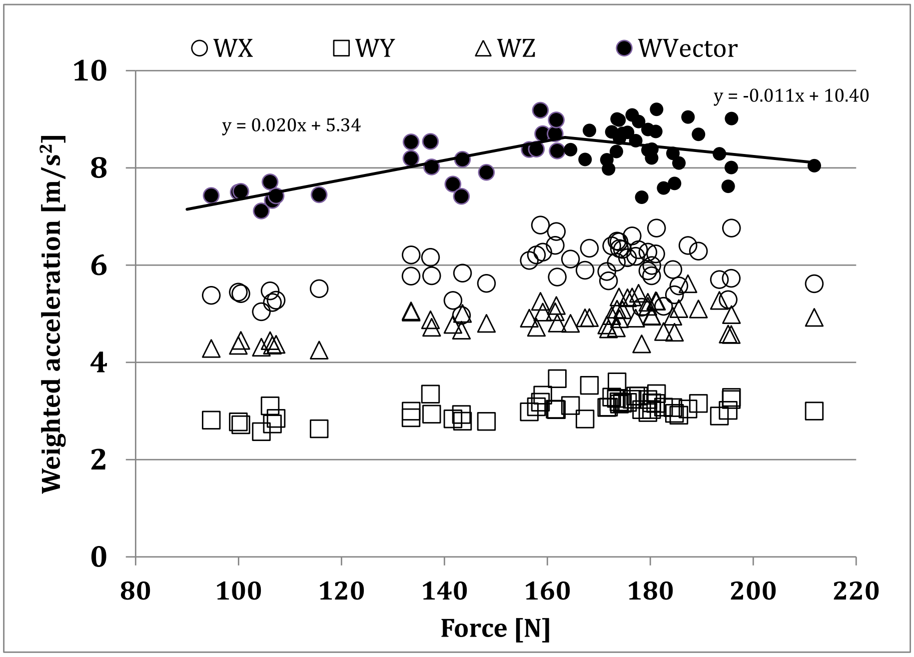

Fig. 3. Weighted acceleration (a_{hv}) values for each axis and for the vector sum plotted by feed force. The inflection point for the vector sum data is at 163.4 N.

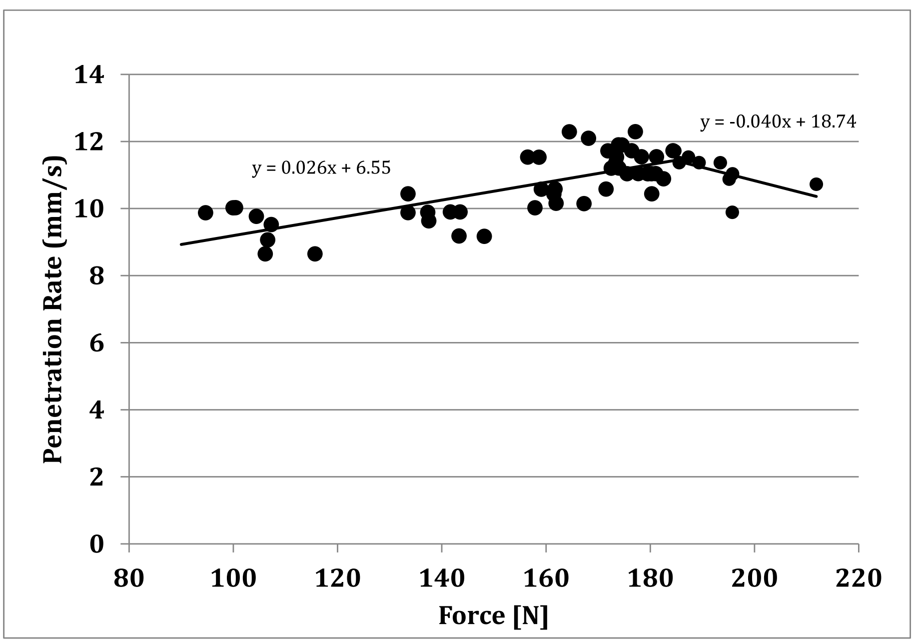

Fig. 4. Drilling penetration rate (mm/s) by feed force for each hole drilled. The inflection point is at 184.7 N.

vector vibration level that is used to estimate allowed minutes of exposure per day are based on the leg 1 of the optimal spline regression equations (Table 1). The penetration rates at 160 and 90 N, are, respectively, 10.82 and 8.89 mm/s; which indicates a higher productivity with the higher FF. The time to reach the ISO Action Limit (T_v) ranged from 41.1 min ($a_{hv} = 8.54$ m/s^2 for an applied FF of 160 N) to 58.8 min ($a_{hv} = 7.14$ m/s^2 for an applied force of 90 N). However, if exposure time for safe drilling is also considered, T_v, then the maximum daily productivity, in total drilling depth per day, is 26.4 m for a FF of 160 N and 31.4 m for a FF of 90 N. In other words, daily productivity is 17% higher with the lower applied FF than the higher applied FF. If productivity is expressed as number of 60 mm deep holes that can be safely drilled per day, then the difference is 523 holes at 90 N of FF versus 440 holes at 160 N FF.

4. Discussion

For the rotary hammer drill and the bit studied, the greater the feed force (FF), from approximately 90 to 160 N, the greater the unweighted and weighted total handle vibration (a_{hv}). Over this range, the estimated weighted total handle vibration (a_{hv}) increased significantly ($p < 0.001$). However, when the FF was increased from approximately 160 to 210 there was no significant change in handle vibration ($p = 0.17$). Along each axis, the pattern of change in acceleration with FF was similar. This mechanical behavior is likely due to variation in stiffness of the system with the compression force (push force applied in the

Table 1
Simple linear and optimal spline models for unweighted and weighted vector sum vibration and penetration rate with independent variable of FF. For the optimal spline fit, the location of the knot (e.g., inflection point) was based on optimizing the adjusted R^2.

	Knot	Intercept	Slope	p-value slope change	p-value slope	Adj R^2
Unweighted Vector Vibration (m/s^2) - Simple Linear Model						0.391
Leg 1	—	78.40 ± 3.33	0.122 ± 0.020	—	<0.001	
Unweighted Vector Vibration (m/s^2) - Optimal Spline Model						0.581
Leg 1	—	63.09 ± 4.80	0.242 ± 0.037	—	<0.001	
Leg 2	160.4 ± 5.4 N	117.95 ± 4.77	−0.100 ± 0.056	<0.001	0.08	
Weighted Vector Vibration (m/s^2) - Simple Linear Model						0.284
Leg 1	—	6.56 ± 0.36	0.011 ± 0.002	—	<0.001	—
Weighted Vector Vibration (m/s^2) - Optimal Spline Model						0.416
Leg 1	—	5.34 ± 0.52	0.020 ± 0.004	—	<0.001	—
Leg 2	163.4 ± 6.8 N	10.40 ± 0.52	−0.011 ± 0.008	<0.001	0.17	—
Penetration Rate (mm/s) - Simple Linear Model						0.466
Leg 1	—	7.16 ± 0.52	0.022 ± 0.003	—	<0.001	—
Penetration Rate (mm/s) - Optimal Spline Model						0.534
Leg 1	—	6.55 ± 0.54	0.026 ± 0.003	—	<0.001	—
Leg 2	184.7 ± 5.1 N	18.74 ± 0.53	−0.040 ± 0.027	0.019	0.149	—

direction of the longitudinal axis of the tool). Hence, propagation increases in all directions when the FF increases up to approximately 160 N. However, when the FF increases from 160 N to 210 N the vibration magnitude remains relatively constant in each direction. The absence of variation within this range of FF likely corresponds to the range of interaction between the power of the tool and the FF. As the FF is increased above 160 N, then the compression force is likely to limit the vibration magnitude as the power of the tool is less able to produce the percussive motion (Kivade et al., 2015). The adjusted correlation coefficient (R^2) for fit of the optimal spline model to weighted vibration was moderate (0.416); the variation is likely due to regional differences in cement aggregate in the block encountered by the bit during drilling.

To the best of our knowledge, only one other study has evaluated the effects of FF on concrete hammer drilling penetration rate and handle vibration. Uhl et al. (2019) measured handle vibration first while 3 workers were instructed to drill into concrete with “low” and “high” FF and, second, while a robot drilled into concrete. No feedback was provided to the workers on the force they applied. The rotary hammer drill and 12 mm diameter bit used weighed approximately 4.5 kg, which is approximately half the mass of the drill and bit used in our study. The drill internal vibration dampening systems differed as well. When the workers drilled horizontally, the mean applied “low” FF was approximately 90 N and the “high” force was approximately 180 N. During the robot drilling part of their study the two levels of FF applied were 80 and 225 N. During manual drilling, the median weighted vector sum handle vibration was 10.0 and 13.0 m/s^2, for the “low” and “high” FF, respectively, while for the robot the values were 4.6 and 7.5 m/s^2. The increase in vibration levels with increase in FF were approximately twice those observed in our study. These differences are likely due to differences in drills used and the design of the robotic systems.

In our study, increasing FF from approximately 90 to 180 N increased the penetration rate and from approximately 180 N up to the maximum feed force tested of 211 N there was little change in penetration rate. Again, this lack of increase in penetration rate above 180 N is likely due to the FF exceeding the power of the drill to generate the percussive motion. In the Uhl et al. (2019) robotic study, increasing FF from 80 to 225 N increased penetration rate from approximately 7.0 to 8.2 mm/s. These lower penetration rates, compared to our study, may be due to the smaller size of their drill. Studies using pneumatic drills during rock drilling have observed a rise then a fall in penetration rate with increasing feed force (Kivade et al., 2015).

When considering the ISO recommended maximum daily exposure time based on the estimated handle vibration levels associated with a FF of 90–160 N, an unexpected finding was that the greatest productivity in total depth of concrete drilled per day occurred at the lowest FF. Approximately 520 holes could be safely drilled at 90 N of FF but only 440 holes could be safety drilled at 160 N. When the ISO standard was applied to the Uhl et al. (2019) data the conclusions were similar.

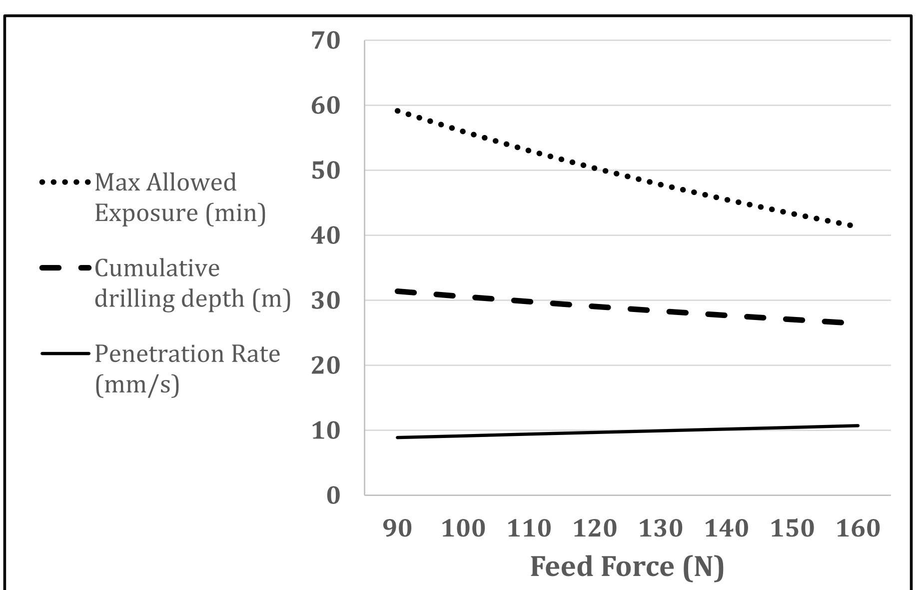

Fig. 5. Relationship of feed force (N) to estimated drilling penetration rate (mm/s), maximum exposure (min) allowed per day per ISO 5349, and cumulative depth drilled per day (m). Estimated penetration rate is based on the equation of Table 1.

Applying an 80 N FF was associated with a safe drilling depth of 59.5 m per day while a FF of 225 N force was associated with a safe drilling depth of 26.2 m. Hence, the present results and those from Uhl et al. (2019) converge to suggest that push forces should be within the 90–100 N range to optimize productivity while maintaining a safe exposure to tool vibration.

Our study did not investigate the effects of FF on transmission of vibration to the fingers and hand. Based on the research of Dong et al. (2005) increasing grip force on a vibrating handle will increase transmission of vibration to the fingers, hand and wrist (Dong et al., 2005) and will, therefore, increase the risk of hand-arm vibration disorder (ISO, 2001;ACGIH, 2020). Increasing FF will increase palmar push force and will likely also increase transmission of vibration to the hand and wrist and increase the risk of hand-arm vibration syndrome (Dong et al., 2010; Pan et al., 2018).

Maximum push forces have been recommended based on psychophysical studies for pushing a cart (Snook and Ciriello, 1991). These recommendations can also be applied to pushing a drill. According to these well recognized guidelines, for a hole that takes 7 s to drill, the maximum recommended applied push force, to accommodate 75% of males, is 170–190 N depending on whether a hole is drilled every minute or every 5 min, respectively. To accommodate 75% of females, the maximum recommended push forces are 100–120 N, respectively. These push force values assume that the handle is at an optimal height near the waist and that the push is in the horizontal, forward direction. When pushing a drill in non-optimal postures or another direction the maximum recommended push forces will be different. For example, to achieve the same FF when drilling vertically upward, the applied push force would have to be at least 100 N more than horizontal drilling in order to also support the mass of the drill and bit (10 kg).

Independent of the human vibration exposure, every type of hammer drilling requires knowledge of optimizing FF, hammer frequency and other parameters relative to the material cut, bit type, cooling, etc. In order to achieve good productivity without causing excessive vibration and increasing bit wear (Flegner, 2016; Shunmugesh and Panneerselvam, 2016). Improper choice of hammer drilling conditions, such as with an excessive FF will cause excessive bit or tool wear, whether drilling into rock or concrete, and will reduce the productivity of the process and increase operating costs.

Several limitations of the study should be acknowledged. First, a test bench system was used to measure handle vibration during testing, but ISO 28927–10 requires workers, not a robotic machine, to perform the drilling. However, the requirements of our study, to obtain precise control of FF, would have been extremely difficult with humans doing the drilling. The test bench system minimized variance in FF compared to having humans doing hammer drilling (Uhl et al., 2019). In addition, the ISO standard requires hammer drilling to be done in the downward not the horizontal direction. In our study, the drilling was done in the horizontal direction in order to prevent binding of the bit. It may be that drilling upward or downward would lead to a different relationship between FF and vibration pattern at the handle.

Finally, only one rotary hammer drill and bit type was studied; other hammer drills and bits may produce different findings (Uhl et al., 2019). The range of handle vibration levels generated by hammer drills is large ($a_{hv} \approx 5–25$ m/s^2, HSE, 2005) and this variation is due to the power source (electricity vs compressed air), material drilled, bits size, drill mass, hammer frequency, vibration dampening system, and other factors. While it is likely that the overall findings here can be applied to other hammer drills, other drills should be studied to confirm the findings.

Based on these findings, there are design modifications to hammer drills that could be made by the manufacturers to optimize productivity while minimizing handle vibration. For example, if an excessive FF is applied the hammering could stop or audible warning sound could be emitted. Construction contractors and workers should be informed that the lowest operational FF required to achieve good concrete cutting will be optimal in term of productivity and safety and the grip force applied should be the least necessary to achieve stable drilling. These recommendations can be made to construction workers during apprenticeship and tailgate trainings and should be included in the instructions provided by rotary hammer drill manufacturers. A video may be a good method for training workers on proper hammer drilling technique. However, to change behavior, it may be necessary to provide a training drilling station that allows workers to hammer drill into concrete while they can simultaneously observe the drill handle vibration level and the penetration rate so that they can directly experience the how their drilling technique influences both.

5. Relevance to industry

Rotary drill manufacturers and construction contractors should inform workers that when drilling into concrete, the lowest exposure to harmful hand vibration occurs when the lowest force is applied to the drill that still produces stable cutting. This force also corresponds to the best overall productivity.

CRediT authorship contribution statement

Lucia Botti: Investigation, Formal analysis, Writing - original draft, Analysis, Writing - original draft. **Bernard Martin:** Methodology, Writing - review & editing. **Alan Barr:** Investigation, Formal analysis, Analysis, Writing - review & editing. **Jay Kapellusch:** Formal analysis, Analysis, Writing - review & editing. **Cristina Mora:** Supervision, Writing - review & editing. **David Rempel:** Conceptualization, Supervision, Methodology, Formal analysis, Writing - original draft, Analysis, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements and Disclaimers

This study was supported in part by a grant from The Center for Construction Research and Training (CPWR) and NIOSH (U60-2-OH009762). The findings and conclusions are solely those of the authors and do not necessarily represent the official views of CPWR or NIOSH. Mention of product names does not imply endorsement. The authors identify no conflicts of interest in the conduct of the study.

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