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Laboratory Surrogate Hammer-Drilling for Reproducible Testing of Design Effects

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SUMMARY

This paper evaluates laboratory surrogate hammer-drilling tasks to impose user load, and thus user strain, in a reproducible manner and comparable to hammer-drilling application. A six-axis industrial robot reproduces the key degrees of freedom of a representative snapshot of the drilling process, and user feedback is used to regulate the target load reproducibly across trials. The resulting measures are benchmarked against data from comparable hammer-drilling application studies. The selected task will be used in a future study for rapid, reproducible testing of power-tool design variants.

KEYWORDS

User-centered design, human-machine interaction, robot, power tools, product ergonomics

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Introduction

Repetitive use of power tools in construction (e.g., rotary hammers) exposes workers to established risk factors for work-related musculoskeletal disorders (WMSD), including high external forces, awkward and often quasi-static upper-extremity postures, and hand-arm vibration (NIOSH, 2024; Charles et al., 2018). From an ergonomics and product-development perspective, addressing these risk factors in tool design is challenging and resource-intensive because usability/ergonomics evaluation commonly relies on iterative prototype build-test cycles and repeated user studies across development stages (Helmstetter et al., 2022; Sauer et al., 2010). In addition, exposure during real power-tool operation is strongly situation-dependent and arises from the coupled interaction of user, tool, and environment. Workplace guidance for hand-transmitted vibration measurement explicitly highlights the need for representative measurements because operating conditions vary in practice (ISO 5349-2:2001). On the user side, users differ in handling strategies (push, grip, and lateral forces) as well as posture and fatigue development. Those are factors that have been shown to modify vibration at the tool–hand interface and task outcomes in hammer drilling and related hand-arm vibration contexts (Lindenmann et al., 2021; Uhl et al., 2021; Pan et al., 2017).

This high variability complicates the detection of statistically significant effects of design changes on user strain because both between-user and within-user differences act as confounders. These sources of variability can dominate the measurement variance and thereby obscure comparatively small design effects. Consequently, laboratory simulations have shown that upper-extremity loading is sensitive to drilling configuration (Anton et al., 2001; Maciukiewicz et al., 2016). In addition, hammer-drill studies have quantified the strong influence of posture and human interaction forces on relevant outcomes (Lindenmann et al., 2021; Uhl et al., 2021).

To investigate the effects of specific design parameters in isolation, with reduced confounding and without overlapping effects (e.g., changing handle position also shifts the center of mass), the Human–Machine Laboratory (HMS-Lab) was introduced for rapid physical testing of power-tool design variants (Saurbier et al., 2025). However, it remains unclear how a surrogate task should be designed to closely replicate hammer-drilling load and strain while still being controlled and reproducible enough to minimize confounders and reliably detect design effects. From this problem, we derived the following research question (RQ): *How accurately do selected laboratory-based surrogate hammer-drilling tasks reproduce user load and strain during horizontal hammer drilling, and which is best suited for reliably assessing design changes on user strain?*

Materials and Methods

To answer this question, we evaluate three laboratory-based surrogate tasks in a small experimental study, comparing user load and strain with data from hammer-drilling studies.

Laboratory setup

Figure 1 shows the setup of the surrogate horizontal hammer drilling use case of the study.

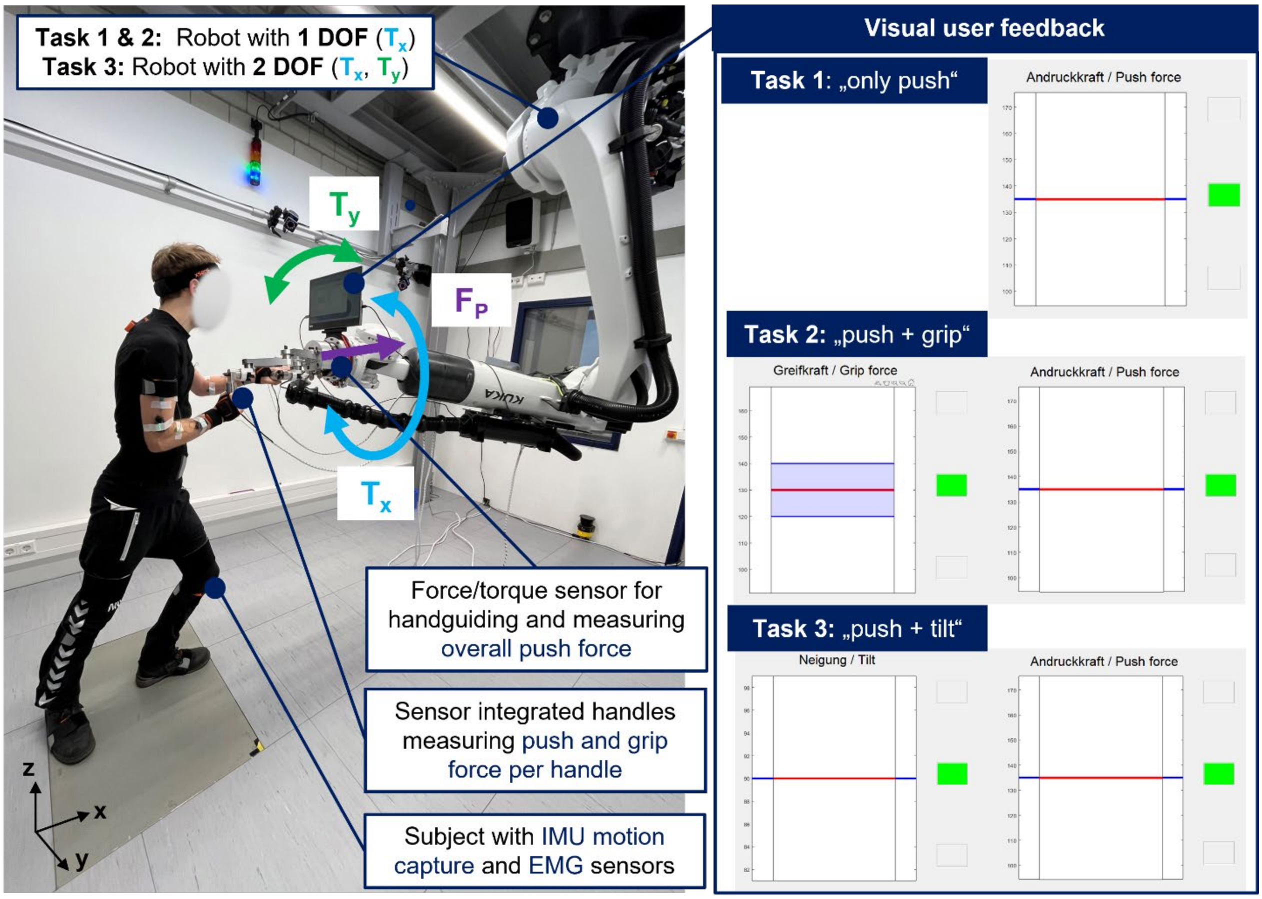


Figure 1: Setup of surrogate tasks in the HMS-Lab (Saurbier et al., 2025) with robot DOF: torque/rotation about x-axis (T_x), torque/rotation about y-axis (T_y), push force in x-direction (F_p).

A six-axis industrial robot (KUKA KR 210 R3100-2C; KUKA AG, Augsburg, Germany) was used to simulate the degrees of freedom (DOF) of a rotary hammer within a bore hole. Two handles were mounted to the robot flange to enable physical interaction with the subject. A 6-axis force/torque sensor (FT Omega 160 DAQ, S/N FT55771; Schunk SE & Co. KG, Lauffen, Germany), installed between the robot end effector and the handles, allowed participants to freely guide the robot via force-velocity control. In this study, the robot’s DOFs were constrained, except two global rotations could be left free: (i) rotation about the drilling axis (task 1-3) and (ii) a limited rotation to impose gravitational torque (task 3). The investigated tasks represent a quasi-static snapshot of a horizontal hammer drilling application. Feed progression and lateral tilting were not considered to get less variety in user measures.

We investigated three different surrogate tasks to simulate the main load during horizontal hammer drilling with minimize confounders due to tool handling (s. Table 1). **For task 1**, the subjects had to maintain an overall push force (low: 90 N, mid: 135 N) during the measurements using digital real-time user feedback (s. Fig. 1). The selected push forces are comparable to horizontal hammer drilling applications (Lindenmann et al., 2021; Saurbier et al, 2026). **For task 2**, the subjects had to additionally maintain an overall grip force (130 N), also derived from Lindenmann et al. (2021) and provided as digital real-time user feedback. The real-time digital grip-force feedback displayed to participants represented the summed grip forces across both handles, the left-right force distribution was not constrained. During pre-tests, we found that requiring participants to monitor more than two feedback variables substantially increased cognitive load and made it nearly impossible to maintain target values reproducibly over the specified time interval. **For task 3**, the subjects had to maintain the overall push force and additionally hold the handles in a stable horizontal alignment, analogous to straight drilling. Real-time digital feedback was provided for both variables. The robot additionally applied a constant gravitational torque based on the weight-induced moment of a Hilti TE 2 rotary hammer (Hilti AG, Schaan, Liechtenstein) measured at half drilling depth with a 12 mm bit (dynamometer force × lever arm), resulting in 0.8 Nm. The combined task "push + grip + tilt" was not tested because it would have required monitoring more than two feedback signals.

Table 1: Task conditions by enabled robot degrees of freedom (DOFs) and digital user feedback.

No	Task	Robot DOF Tx	Robot DOF Ty	Push-force user feedback	Grip-force user feedback	Tilt user feedback
1	***Only push-force feedback*** *(only push)*	x		x		
2	***Grip force-feedback*** *(push + grip)*	x		x	x	
3	***Mass-torque simulation*** *(push + tilt)*	x	x	x		x

Study procedure

The study was conducted with three healthy, right-handed participants (two female, one male; age 26–28 years). Body height ranged from 165-182 cm and body weight from 60-89 kg. Maximum two-handed push force ranged from 152–362 N, and maximum grip force ranged from 170–219 N for the left hand and 249–257 N for the right hand. All participants volunteered to take part, provided informed consent, and were informed about the experimental procedure in advance. The experiment could be paused or terminated at any time. All collected data were anonymized. The three simulated drilling task conditions were performed in randomized order. Each trial lasted 15 s and was repeated three times. The following physical measures were recorded during the surrogate drilling trials:

1. **Posture / joint angles** were measured using an inertial motion capture system (17 IMUs; Xsens Awinda, Movella Inc., El Segundo, USA; 60 Hz). To ensure comparability of posture across participants, the working height was adjusted to individual body height (approximately chest height).
2. **Interaction forces** comprised (a) total push force measured with the 6-axis force/torque sensor at the robot end effector, (b) push force per handle measured with one 3-axis piezoelectric force sensor integrated in each handle (type 9317C, Kistler Instrumente AG, Winterthur,

Switzerland), and (c) grip forces measured with two single-axis piezoelectric force transducers per handle (auxiliary handle: type 9001A; main handle: types 9011A/9011C; Kistler Instrumente AG, Winterthur, Switzerland). The grip force sensors were integrated between two aluminum handle halves with the split plane aligned perpendicular to the push force direction, as specified in DIN EN ISO 10819:2022-12. All force signals were sampled at 4000 Hz.

3. **Electromyography (EMG)** was recorded bilaterally from shoulder and arm muscles using Delsys Trigno Duo sensors (Delsys Inc., Natick, MA, USA; 2148 Hz). The following muscles were measured: anterior deltoid (AD), lateral deltoid (LD), biceps brachii (BB), triceps brachii (TB), flexor carpi radialis (FCR), and extensor carpi radialis (ECR). The sensor placement and measurement preparation were based on the SENIAM guidelines (Hermens et al., 1999). For normalization, muscle-specific maximum voluntary contraction (MVC) tests were performed twice per muscle prior to the simulated drilling trials.

All measurement systems were synchronized and triggered using an ADwin Pro II real-time measurement system (T12, Jäger Computergesteuerte Messtechnik GmbH, Lorsch, Germany).

Data analysis

Data were segmented using a threshold of 90 % of the predefined target push force. Joint angles were low-pass filtered at 6 Hz, and interaction forces at 10 Hz (second-order Butterworth). For each trial, mean joint angles and mean grip forces were computed over the segmented interval. EMG was onboard bandpass filtered with 20-450 Hz, DC-offset corrected, their amplitude was quantified as root mean square (RMS) per trial, and values were normalized to MVC by dividing by the muscle-specific maximum MVC RMS (EMG in %MVC). Joint angles and normalized EMG (low push force), grip forces (medium push force), and the push-force distribution between the auxiliary and main handle were compared across surrogate task 1-2 and against laboratory hammer-drilling applications (Rack et al., 2025; Sutschet et al., 2025; Lindenmann et al., 2021; Saurbier et al., 2026). Reproducibility across repeated trials was assessed via intraclass correlation coefficients (ICC) for joint angles and grip forces. However, ICC values were interpreted cautiously due to the small subject number (n = 3) and only used as a supportive metric. All post-processing was performed in MATLAB (R2024b, MathWorks, Natick, MA, USA) and IBM SPSS Statistics (version 29.0.2.0, IBM Corp., Armonk, NY, USA).

Results and Discussion

Reproducible assessment of user strain requires a surrogate task that reproduces the biomechanical load of a hammer-drilling application (posture, interaction forces). Accordingly, we first analyze posture, grip forces, and push force distribution between handles followed by the resulting muscle activation (EMG %MVC).

1. Posture (joint angles)

Across surrogate task 1-3, posture and shoulder/upper-arm muscle activation fell within a similar range and were broadly comparable to the hammer-drilling application (s. Fig. 2). Neither additional mass-torque nor specified grip force cause a change in shoulder, elbow and wrist joint angles. Relative to the hammer-drilling application, the main deviations occur at the left shoulder (abd/add) and left wrist (flex/ext, abd/add). Overall, the surrogate tasks elicit less shoulder abduction, a more extended shoulder-arm posture, and greater left-hand abduction angles. Most variability in joint angles can be explained by individual posture strategies, as participants were free to choose their stance, specifically the handle orientation about the x-axis and their distance to the handles. Intra-individual variability was low (ICC > 0.75 for most joint angles).

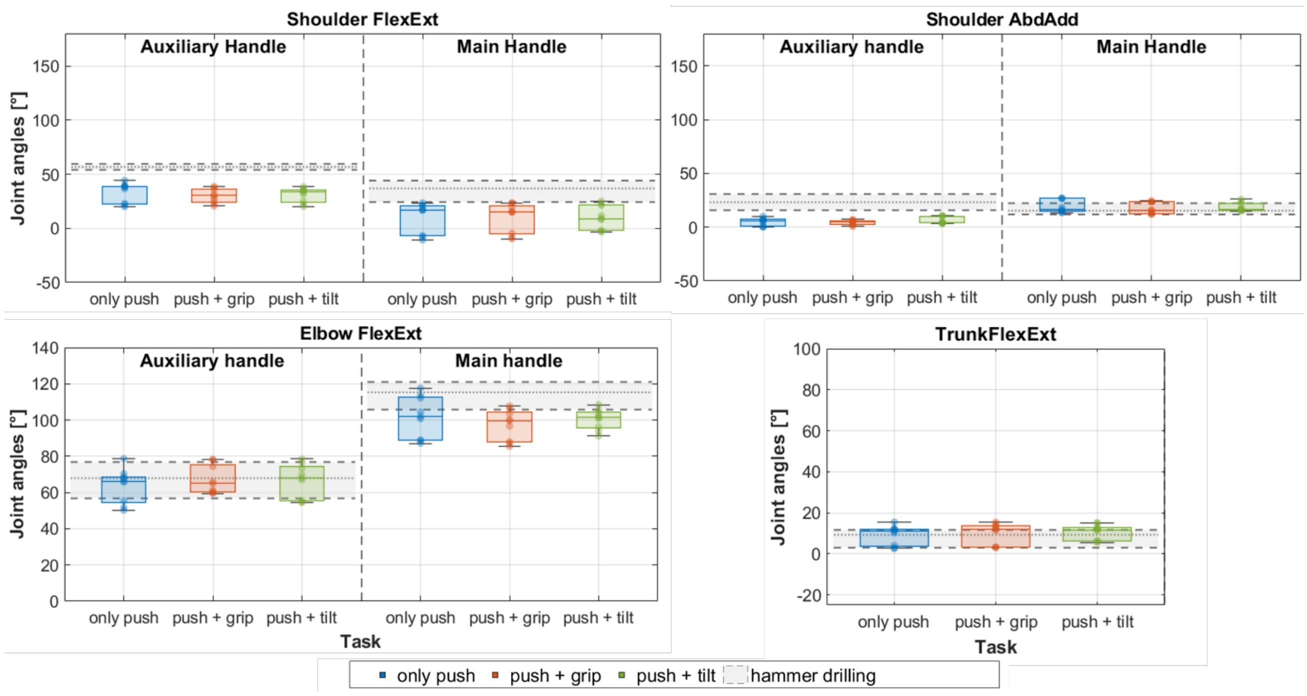


Figure 2: Joint angles at low push force (90 N) for surrogate tasks 1-3 vs. hammer drilling (Rack et al., 2025; Sutschet et al., 2025), shown for the auxiliary (non-dominant) and main (dominant) handle. Boxplots show median, Q1, and Q3 (N = 9).

2. Interaction forces (grip and push forces)

Grip forces. Figure 3 indicates a handle-specific trade-off: with grip-force feedback, main-handle grip was closer to the hammer-drilling application, whereas the auxiliary handle matched better without feedback. This aligns with the feedback implementation, which displayed summed grip force across both handles (not handle-specific targets), allowing participants to redistribute grip to meet the overall target (Fig. 3). Trigger actuation was omitted; although it can add ~40 N at the main handle (Lindenmann et al., 2021), it is unlikely to explain the deviations, especially since Rack et al. (2025) also excluded trigger operation. More than two concurrent feedback signals were impractical because participants already monitored two displays. Given its relevance for user strain, grip force should therefore be controlled or at least monitored. ICC values were again interpreted cautiously due to the small subject number and intentionally reduced between-subject variability from the target-force instruction. Repeatability was assessed mainly via distribution plots and within-subject dispersion, which was generally good. For the low push forces, agreement ranged from very good (“only push”, left handle: ICC(3,1) = 0.916) to poor (“push + tilt”, left handle: ICC(3,1) = −0.039).

Push forces. Push-force distribution was more symmetric than in Rack et al. (2025). Across surrogate tasks, ratios were consistent (low ≈40:60, mid ≈30:70; auxiliary:main), indicating a shift toward the dominant hand with increasing push demand, unlike the ≈10:90 ratio reported by Rack et al. at low push force. Besides handling roles (main: power transmission; auxiliary: stabilization), methodological differences may explain the discrepancy: PLA-based sensor integration in Rack et al. likely added compliance and lever-arm moments, increasing disturbance sensitivity and reducing force accuracy relative to the present aluminum mount.

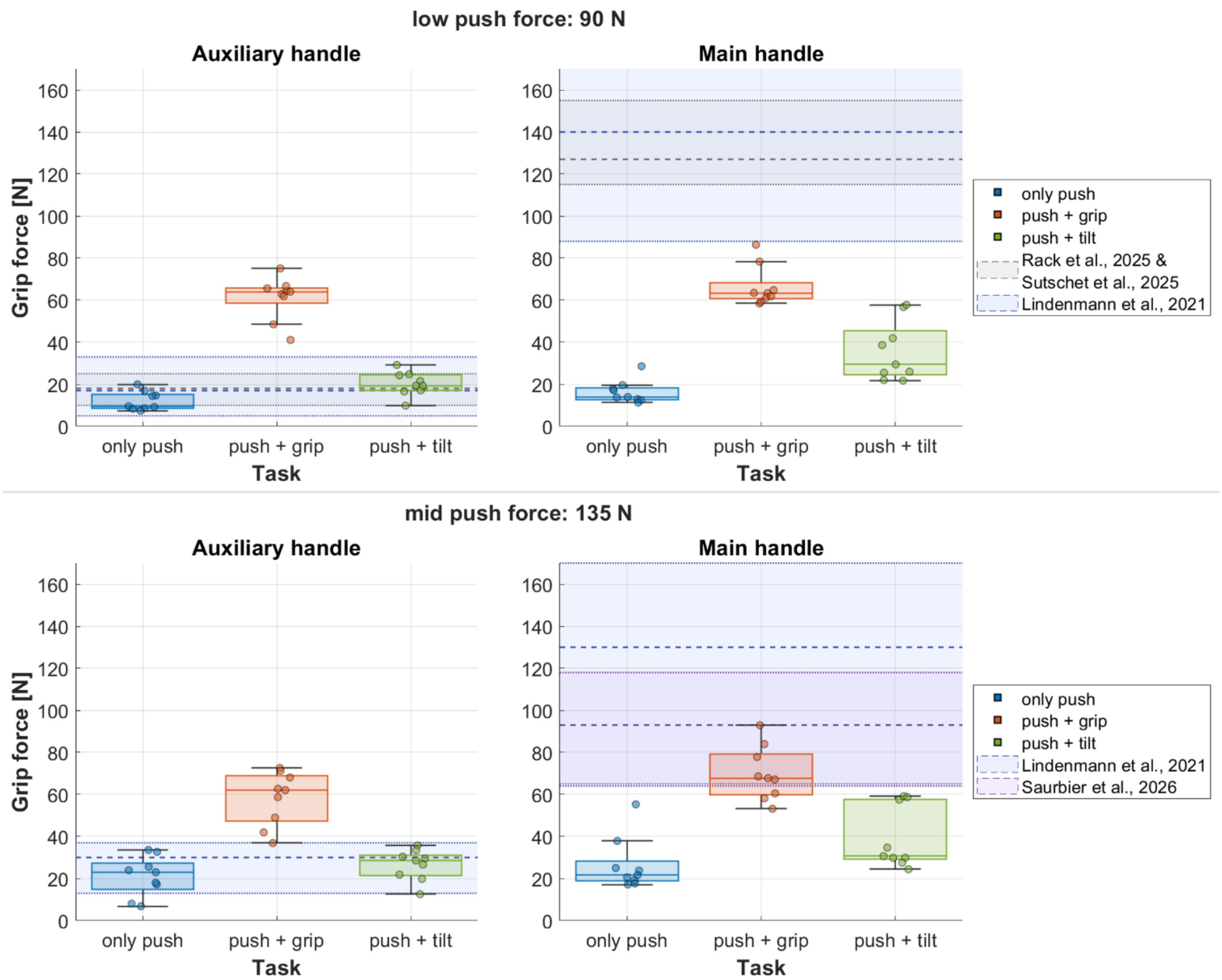


Figure 3: Grip forces at low push force (upper row) and medium push force (lower row) for surrogate tasks 1-3 vs. hammer drilling, shown for the auxiliary (non-dominant) and main (dominant) handle. Boxplots show median, Q1, and Q3; dots show individual measurements (N = 9).

3. Electromyography (EMG)

The EMG comparison between the surrogate tasks and the reference study is shown in Figure 4 (%MVC boxplots) and Figure 5 (heatmaps of absolute deviations from the hammer-drilling reference median) per muscle and handle.

Overall, EMG levels of the shoulder and upper-arm muscles (AD, LD, BB, TB) were close to the hammer-drilling application for both handles, with only small deviations between surrogate tasks. In contrast, the forearm showed the most systematic deviation, most prominently for FCR, across tasks and handles. Among the surrogate tasks, task 2 (with grip-force feedback) yielded the closest agreement, which is plausible given the strong coupling between forearm activation and grip demand. In addition, hand-arm vibration has been shown to increase EMG activity in upper-extremity muscles, including forearm flexors/extensors and shoulder/neck musculature, via reflexive responses and stabilizing co-contraction, with effects depending on posture and loading (Rohmert et al., 1989). This mechanism may contribute to residual differences in forearm EMG relative to the hammer-drilling application, even when posture and target push force are largely controlled.

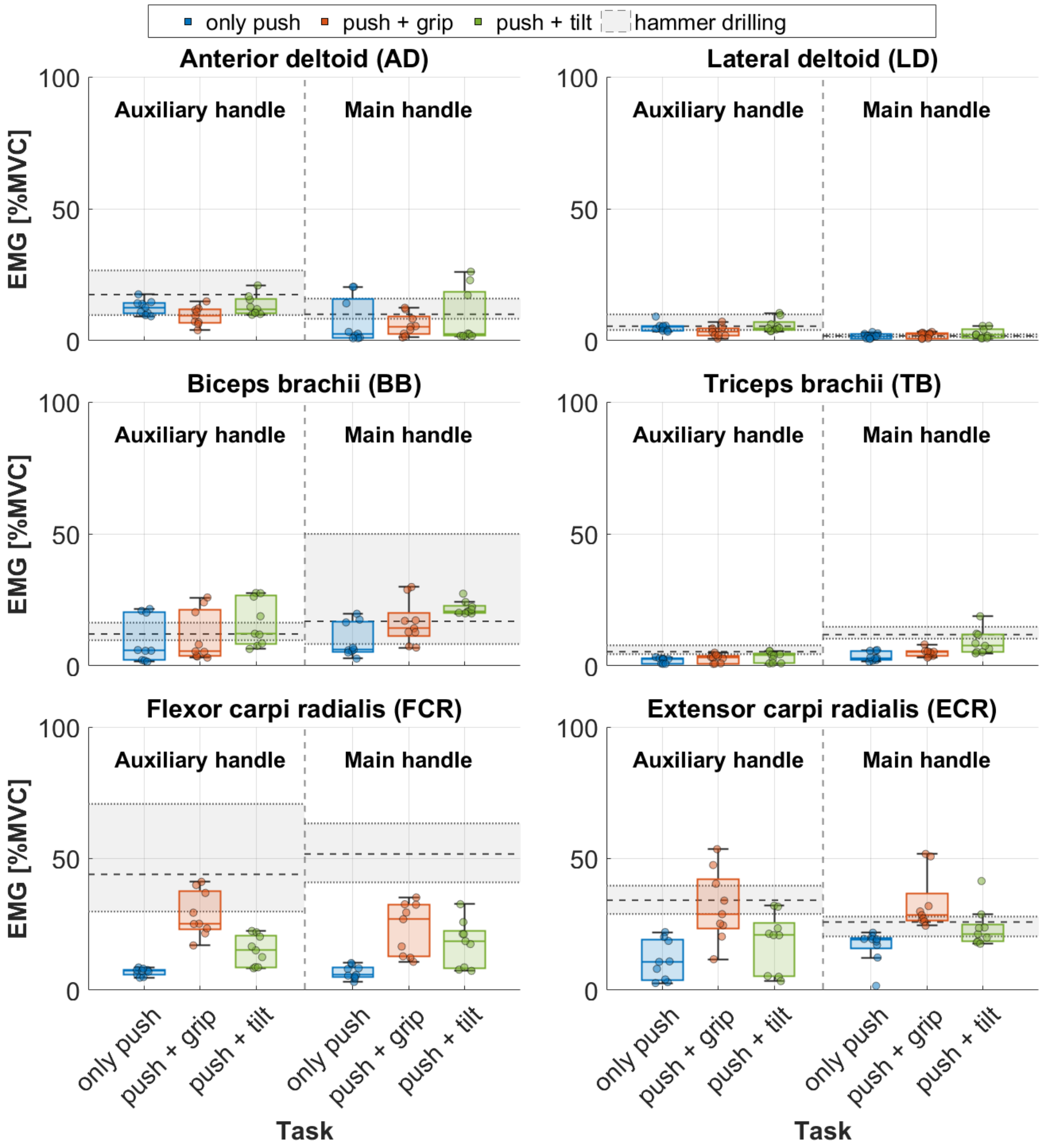
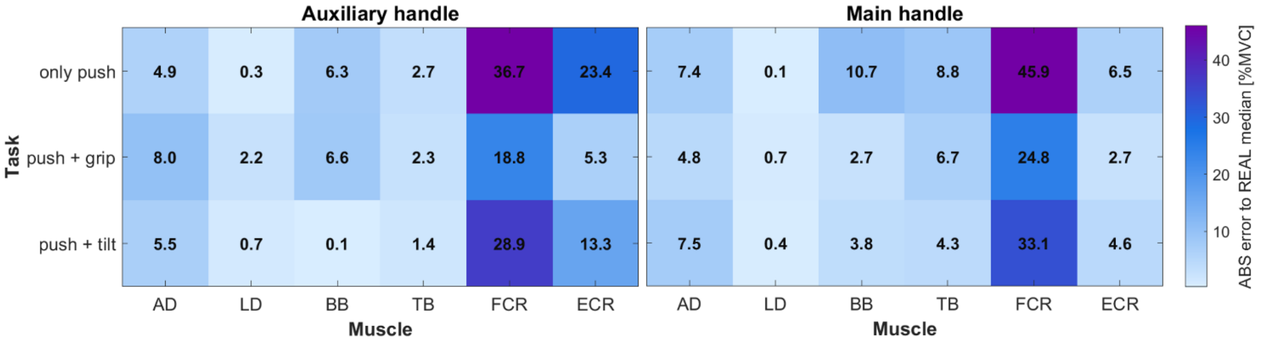


Figure 4: EMG (%MVC) values at low push force (90 N) for surrogate tasks 1-3 vs. hammer drilling (Rack et al., 2025; Sutschet et al., 2025), shown for the auxiliary (non-dominant) and main (dominant) handle. Boxplots show median, Q1, and Q3; dots show individual measurements (N = 9).



Auxiliary handle

Task	AD	LD	BB	TB	FCR	ECR
only push	4.9	0.3	6.3	2.7	36.7	23.4
push + grip	8.0	2.2	6.6	2.3	18.8	5.3
push + tilt	5.5	0.7	0.1	1.4	28.9	13.3

Main handle

Task	AD	LD	BB	TB	FCR	ECR
only push	7.4	0.1	10.7	8.8	45.9	6.5
push + grip	4.8	0.7	2.7	6.7	24.8	2.7
push + tilt	7.5	0.4	3.8	4.3	33.1	4.6

Figure 5: Absolute errors of EMG (%MVC) values for surrogate task 1-3 vs. hammer drilling (Rack et al. 2025; Sutschet et al., 2025).

Regarding reproducibility, within-subject repeatability across the three repetitions was generally good. In contrast, inter-individual variability in EMG (%MVC) is usually driven by differences in anthropometrics and participants' strength/training status.

Limitations

Prescribing push and grip forces produced a realistic representation of user load and strain during hammer drilling. However, for investigations targeting different power-tool designs, this approach constrains the analysis of how users would naturally adapt their push and grip strategies in response to design changes. Moreover, certain degrees of freedom (e.g., unintentional tool tilting) were intentionally restricted to reduce confounders. Thus, the current task set is not suited to study handling effects and would need to be adjusted for that purpose. Vibration, known to influence EMG (Rohmert et al., 1989; Frattini et al., 2009), was deliberately excluded, because design changes (e.g., handle position/orientation) would alter vibration exposure at the handles and posture would further modulate its impact on EMG, complicating interpretation. Finally, the sample size was small because this study served as a pre-test for a larger subject study. Nevertheless, participants reflected a typical female and male user profile.

Conclusion

This work compares surrogate hammer-drilling tasks for imposing user load and thus user strain in a reproducible manner and comparable to hammer-drilling application. Across the investigated surrogate tasks, prescribing total push and grip forces yielded the closest agreement with hammer-drilling application data, particularly for main-handle grip force and forearm EMG, while upper-extremity joint angles differed only marginally between tasks. Remaining deviations from application studies are likely due to altered power distribution and missing handling effects. Based on these results, surrogate task 2 with grip-force feedback was selected as a basis for subsequent studies on disruptive rotary-hammer design variants (e.g., handle position and orientation), enabling rapid and reproducible laboratory testing in which individual design parameters can be varied in isolation without introducing additional system changes (e.g., shifts in the center of mass).

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Conflict of Interest: The authors declare no conflict of interest. The funders had no role in the study design; in the collection, analysis, or interpretation of data; in manuscript writing; or in the decision to publish.

Ethics Approval: The study was approved by the Ethics Committee of Karlsruhe Institute of Technology (Application Number: A2025-015; approved 15 April 2025).

AI / Language Assistance: Language was refined using DeepL and ChatGPT (GPT-5.2). The authors reviewed and edited the content and take full responsibility for the publication.

Author Contributions: Study setup: S. Sutschet. Methodology: S. Sutschet, R. Rack. Data acquisition: S. Sutschet, R. Rack. Data analysis: S. Sutschet, R. Rack. Writing - original draft: S. Sutschet, R. Rack. Writing - review & editing: S. Saurbier. Supervision: K. Bengler, S. Matthiesen. Funding acquisition: K. Bengler, S. Matthiesen.

References

Charles, L. E., Ma, C. C., Burchfiel, C. M., & Dong, R. G. (2018). Vibration and ergonomic exposures associated with musculoskeletal disorders of the shoulder and neck. Safety and Health at Work, 9(2), 125–132. https://doi.org/10.1016/j.shaw.2017.10.003

Fratini, A., La Gatta, A., Bifulco, P., Romano, M., & Cesarelli, M. (2009). Muscle motion and EMG activation in vibration treatment. Medical Engineering & Physics, 31(9), 1166–1172. https://doi.org/10.1016/j.medengphy.2009.07.014

Helmstetter, S., Dörr, M., Germann, R., & Matthiesen, S. (2022). User-centered design of power tools: A generic process for evaluation of usability aspects. Engineering Research, 86, 93–104. https://doi.org/10.1007/s10010-021-00546-y

Hermens, H. J., Freriks, B., Merletti, R., Stegeman, D. F., Blok, J. H., Rau, G., et al. (1999). European recommendations for surface electromyography: Results of the SENIAM Project. Roessingh Research and Development B.V. (ISBN 90-75452-14-4). https://www.seniam.org/pdf/contents8.PDF

International Organization for Standardization. (2001). ISO 5349-2:2001 Mechanical vibration—Measurement and evaluation of human exposure to hand-transmitted vibration—Part 2: Practical guidance for measurement at the workplace. International Organization for Standardization. https://www.iso.org/standard/27511.html

Deutsches Institut für Normung. (2022). DIN EN ISO 10819:2022-12 Mechanical vibration and shock—Hand-arm vibration—Measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand (ISO 10819:2013 + Amd. 1:2019 + Amd. 2:2021).

Lindenmann, A., Uhl, M., Gwosch, T., & Matthiesen, S. (2021). The influence of human interaction on the vibration of hand-held human–machine systems: The effect of body posture, feed force, and gripping forces on the vibration of hammer drills. Applied Ergonomics, 95, 103430. https://doi.org/10.1016/j.apergo.2021.103430

Maciukiewicz, J. M., Cudlip, A. C., Chopp-Hurley, J. N., & Dickerson, C. R. (2016). Effects of overhead work configuration on muscle activity during a simulated drilling task. Applied Ergonomics, 53(Pt A), 10–16. https://doi.org/10.1016/j.apergo.2015.08.005

NIOSH. (2024, March 1). Step 1: Identify risk factors. Centers for Disease Control and Prevention. https://www.cdc.gov/niosh/ergonomics/ergo-programs/risk-factors.html

Pan, D., Xu, X. S., Welcome, D. E., McDowell, T. W., Warren, C., & Dong, R. G. (2017). The relationships between hand coupling force and vibration biodynamic responses of the hand-arm system. Ergonomics, 61(1), 1–14. https://doi.org/10.1080/00140139.2017.1398843

Rack, R., Sutschet, S., Bengler, K., & Matthiesen, S. (2025). Influence of disruptive design changes of a hammer drill on user posture and muscle stress: An exploratory study. In 71. Kongress der Gesellschaft für Arbeitswissenschaft e.V. (pp. 1040–1045). Gesellschaft für Arbeitswissenschaft (GfA). https://doi.org/10.5445/IR/1000182705

Rohmert, W., Wos, H., Norlander, S., & Helbig, R. (1989). Effects of vibration on arm and shoulder muscles in three body postures. European Journal of Applied Physiology and Occupational Physiology, 59(4), 243–248. https://doi.org/10.1007/BF02388323

Sauer, J., Seibel, K., & Rüttinger, B. (2010). The influence of user expertise and prototype fidelity in usability tests. Applied Ergonomics, 41(1), 130–140. https://doi.org/10.1016/j.apergo.2009.06.003

Saurbier, S. Y., Helmstetter, S., Sutschet, S., Lindenmann, A., & Matthiesen, S. (2025). The Human-Machine Symbiosis Laboratory: A new testing environment for developing symbiotic human-machine systems. In T. Ahram (Ed.), Human factors in design, engineering and computing: Proceedings of the AHFE International Conference on Human Factors in Design, Engineering, and Computing (AHFE 2025 Hawaii Edition) (pp. 777–786). AHFE International. https://doi.org/10.54941/ahfe1006890

Saurbier, S. Y., Pisarzowski, M., Becker, A., Kleinhans, L., Bunk, L., Krause, D. & Matthiesen, S. (2026). Measurement and evaluation of the interaction forces of specific hammer drilling strategies to determine requirements for dynamic hand-arm models. Manuscript submitted for publication (submitted to the AHFE 2026 International Conference, Istanbul, Turkey).

Sutschet, S., Rack, R., Bengler, K., & Matthiesen, S. (2025). Experimental data and additional evaluation for the paper “Influence of disruptive design changes of a hammer drill on user posture and muscle stress – An exploratory study” [Dataset]. KITopen (RADAR4KIT), Karlsruhe Institute of Technology. https://doi.org/10.35097/d072bjn9s8ghkpah

Uhl, M., Lindenmann, A., & Matthiesen, S. (2021). Analysis of factors influencing the productivity of hammer drilling: User forces, human fatigue, drilling direction, and drill bit. Applied Ergonomics, 92, 103338. https://doi.org/10.1016/j.apergo.2020.103338