Published in final edited form as:
Appl Ergon. 2021 September ; 95: 103454. doi:10.1016/j.apergo.2021.103454.

An investigation of the effectiveness of vibration-reducing gloves for controlling vibration exposures during grinding handheld workpieces

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Abstract

Prolonged and intensive vibration exposures during the grinding of handheld workpieces may cause hand-arm vibration syndrome. The objectives of this study are to develop an on-the-hand method for evaluating vibration-reducing (VR) gloves, and to determine whether VR gloves can significantly reduce the vibration exposures. A worker holding and pressing a typical workpiece (golf club head) against a grinding wheel or belt in order to shape the workpiece was simulated, and the input vibration and those on the workpiece and hand-arm system were measured. Ten human subjects participated in the experiment. The results demonstrate that VR gloves significantly reduced the vibrations at the palm, hand dorsum, and wrist. The grinding interface condition and hand feed force did not substantially affect glove effectiveness. The use of gloves slightly increased the workpiece resonant response, but the resonant response did not significantly affect glove effectiveness. This study concluded that the use of VR gloves can help control vibration exposures of workers performing grinding of handheld workpieces.

Keywords

Hand-arm vibration; Handheld workpiece vibration; Vibration-reducing glove; Anti-Vibration glove

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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.

1. Introduction

The grinding of handheld workpieces is performed in many workplaces (Ikeda et al., 1998; HSE 2005; Kaulbars, 2014; Chen et al., 2015). Daily intensive exposures to the vibrations generated in the grinding of handheld workpieces may cause hand-arm vibration syndrome (Chen et al., 2015). Vibration-reducing (VR) gloves have been used as one of the methods for helping to control these vibration exposures (Jetzer et al., 2003). However, it remains unclear whether VR gloves can effectively reduce the vibrations transmitted from a workpiece to the hand-arm system during the grinding process.

As a preliminary analysis towards the current study, the potential effectiveness of three typical VR gloves (cushion materials: glove 1 - dipped neoprene, glove 2 - gel-filled, and glove 3 - air bubble) for grinding operations was roughly estimated using a transfer function method (Dong et al., 2014). The estimate used the vibration spectra measured on two types of workpieces (titanium-alloy golf club head and stainless-steel golf club head) at a workplace in a previous study (Chen et al., 2017), and the vibration transmissibility spectra of each glove measured at the fingers and palm of the hand using adapter methods or to-the-hand methods (Xu et al., 2019). The results are listed in Table 1. They suggest that the use of VR gloves could substantially reduce the vibrations transmitted to the hands of workers performing grinding of handheld workpieces.

While the workpiece vibration spectra measured at the workplace should be reliable, it is unknown whether the glove vibration transmissibility spectra used in the estimations are representative of those in workpiece grinding because those transmissibility measurements were made with human subjects employing a power grip on a cylindrical handle that is largely different from the posture used during the workpiece grinding process. The glove transmissibility spectra measured using to-the-hand methods may not be fully representative of actual glove effectiveness because such methods measure only the suspension or cushioning functions of the gloves. Furthermore, the use of VR gloves may increase the workpiece vibration because the cushioning function of VR gloves generally reduces the effective mass of the hand-arm system acting on the workpiece. Because no study has focused on this glove effect, it remains unknown whether the increased workpiece vibration could substantially cancel the cushioning effect of VR gloves.

Theoretically, all the above-described deficiencies and issues can be overcome or addressed by conducting an experiment that closely simulates the grinding of handheld workpieces and uses on-the-hand methods to determine the glove vibration transmissibility. Such on-the-hand methods have been most frequently used in the investigations of the effectiveness of VR gloves for reducing finger vibration exposures on cylindrical tool handles (Griffin et al., 1982; Chang et al., 1999; Paddan and Griffin, 2001; Welcome et al., 2014, 2016; Hamouda et al., 2018). While a study used an on-the-hand-dorsum method to examine the effect of a VR glove on the hand vibration in the operations of chipping hammers (Dong et al., 2002), no study has investigated the effectiveness of VR gloves for reducing the vibration responses distributed on the hand dorsum, wrist, forearm and upper arm in the grinding of handheld workpieces.

A laboratory experimental method has been developed to characterize the vibration responses of the entire grinding interface-workpiece-hand-arm system (Xu et al., 2020), which closely simulates the grinding operations and the interactions between a workpiece and the hands. The objectives of this study are to further develop this method for testing and evaluating VR gloves using the on-the-hand approach and to determine whether a typical VR glove can reduce the vibration transmitted to the hand-arm as effectively as that predicted in the preliminary analysis. While the effect of VR gloves on finger vibration responses was examined in another study (Welcome et al., 2018), the current study focused on the effects of VR gloves on the vibrations distributed at the hand dorsum, wrist, forearm, and upper arm. The glove effect on the vibration response of the workpiece and the effects of two major grinding operation factors (feed force and grinding interface conditions) on VR glove effectiveness were also examined in this experimental study. A theory was proposed and presented in the Discussion section to help understand the experimental results.

2. Materials and methods

Ten human subjects (5 males and 5 females) participated in this study with informed consent. Anthropometry data of these subjects was listed in Table 2. The study protocol was reviewed and approved by the NIOSH Institutional Review Board.

2.1. Instrumentation and test setup

The basic instrumentation and test setup were the same as those described in a previous study (Xu et al., 2020). Briefly, the experiment was conducted using a single-axis vibration test system (Unholtz-Dickie, TA250-S032-PB) that can be used to conduct the standard glove test (ISO 10819, 2013). The standard glove test was modified by replacing the instrumented cylindrical handle on the test system with a handle with a flat surface so that a stable directional interaction between the workpiece and the handle interface could be achieved during the simulated vibration exposure, as shown in Fig. 1(a, c). Each subject mimicked the body and hand postures in holding the workpiece against a grinding interface observed at a workplace (Chen et al., 2017), as shown in Fig. 1 (a). The driving wheel of the belt grinding machine usually features a rubber tread (Tönshoff and Degenhardt, 1982). This configuration was simulated using a section of rubber firmly attached to the instrumented metal handle which was rigidly connected to a shaker that provided the source of vibration required in the experiment, as shown in Fig. 1(c). A tri-axial accelerometer (Endevco, 65–100) was installed at the handle center location and used to measure and control the vibration input to the interface. Two force sensors (Kistler 9212) were also installed on the handle to measure the vibration force at the interface.

Each subject stood on a force plate (Kistler, 9286AA), which was used to measure the feed force applied by the subject. The feed force was displayed on a computer monitor placed in front of the subject so that he/she could monitor and control the applied force. The workpiece vibration was measured using a tri-axial accelerometer (PCB 356A11) installed on the workpiece using a screw. As shown in Fig. 1(a), the vibration transmitted to the hand dorsum was measured using an adapter (D) attached on the back of the hand using a Velcro wrap, which was equipped with a tri-axial accelerometer (Endevco, M35). The vibrations transmitted to the wrist, forearm, and upper arm were measured using three adapters (A, B, and C) respectively as shown in Fig. 1(b), and each of which was also equipped with a tri-axial accelerometer (Endevco, M35). Each adapter was secured in place using a cloth wrap, as shown in Fig. 1(a). This adapter method was evaluated in a previous study and proved acceptable for the measurement (Xu et al., 2015). A data acquisition and analysis system (B&K 3050/3053) was used to collect and process vibration and force signals.

2.2. Study variables and test procedures

The vibration excitation spectrum used in this study is illustrated in Fig. 2, which is a band-limited random vibration spectrum with a constant-velocity (0.0128 m/s) section from 6.3 to 300 Hz and a ramp-down section from 300 to 1600 Hz. The spectrum is similar to that recommended in the current standard glove screening test (ISO 10819, 2013), except the low frequency section (6.3 Hz–16 Hz), which was not specified in the standard, was added in this study. As also shown in Fig. 2, the basic trends of the excitation acceleration spectrum (bold line) are similar to those of the workpiece acceleration spectra measured in a previous study (Chen et al., 2017). It should also be noted that the differences between the excitation spectrum and the workpiece vibration spectra are unlikely to substantially change the glove vibration transmissibility, as demonstrated in a few previous studies (Rakheja et al., 2002; Welcome et al., 2012). This justifies the use of the transfer function method to estimate the glove effectiveness listed in Table 1 (Dong et al., 2014). The transfer function method was also used to estimate the glove effectiveness for reducing the vibrations at different locations on the hand-arm system, which is further described later in this paper.

A pair of dipped neoprene gloves, one type of typical VR gloves considered in the preliminary analysis, were selected for this study for the following reasons: (i) the performance of such type of gloves is representative of VR gloves, as indicated in Table 1; (ii) the glove exhibits a high coefficient of friction, which may make it easier for a subject to hold the slippery golf club head during vibration exposure; and (iii) this glove type can be used in the actual workplace grinding of golf club heads. Each of the subjects used the same pair of gloves in the experiment.

Besides the hand conditions (bare hand and gloved hand), two levels of feed force (15 N and 30 N) and three grinding interfaces (R1, R2, R3 in Fig. 1(c)) with different stiffness levels were considered in the current study, which were determined in the characterization of the system responses (Xu et al., 2020). The two force levels were determined based on the hand contact force measured in a previous study at a workplace (Chen et al., 2017). The experimental results suggest that the feed force applied in the grinding of golf club head was generally less than 30 N. Therefore, it is reasonable to use 15 N and 30 N to study the effect of the feed force on the system responses. For each of the twelve test treatments (2 hand conditions × 3 interfaces × 2 feed forces), each subject performed three consecutive trials. However, the test sequences of treatments were independently randomized among the ten subjects. During each test trial, the response measurements started after the subject reached and maintained the pre-defined feed force under the vibration condition; each trial lasted 20 s. The apparent mass (AM = the vibration force acting at the workpiece-handle interface divided by the handle vibration acceleration) and the vibrations on the club head, hand dorsum, wrist, forearm, and upper arm were simultaneously measured and expressed in the one-third octave bands from 6.3 to 1600 Hz. The mechanical impedance (*MI*) was calculated from the measured apparent mass or ($MI = j\omega \times AM$. where $j = \sqrt{-1}$, $\omega = 2\pi f$, and f is vibration frequency).

2.3. Calculations of vibration transmissibility spectra

In the current study, the vibration transmissibility ($T_{L\text{-}Handle}$) at each location (L) on the workpiece-hand-arm system with respect to the system driving point (Handle) was calculated using the total vibration acceleration at the location on the system (A_L) and that on the handle (A_{Handle}):

$$T_{L\_Handle} = \frac{A_L}{A_{Handle}} = \frac{\sqrt{a_{L-x}^2 + a_{L-y}^2 + a_{L-z}^2}}{\sqrt{a_{Handle-x}^2 + a_{Handle-y}^2 + a_{Handle-z}^2}}, \quad L = club\ head,\ hand\ dorsum,\ wrist,\ forearm,\ and\ upper\ arm \tag{1}$$

where $a_{L\text{-}x}$, $a_{L\text{-}y}$, and $a_{L\text{-}z}$ are the tri-axial accelerations measured at the L-location on the system, and $a_{Handle\text{-}x}$, $a_{Handle\text{-}y}$, and $a_{Handle\text{-}z}$ are those measured on the instrumented handle.

The effect of the glove on the vibration response at each location (L) on the hand-arm system can be determined by comparing the transmissibility measured with gloved hands ($T_{GlovedHand\text{-}L\text{-}Handle}$) and that measured with bare hands ($T_{BareHand\text{-}L\text{-}Handle}$), which were calculated using Eq. (1). Their ratio is the location-specific glove vibration transmissibility with respect to handle vibration ($T_{Glove\text{-}L\text{-}Handle}$):

$$T_{Glove-L-Handle} = \frac{T_{GlovedHand-L-Handle}}{T_{BareHand-L-Handle}}, \quad L = hand\ dorsum,\ wrist,\ forearm,\ and\ upper\ arm \tag{2}$$

The vibration transmissibility at any location on the hand-arm system with respect to the workpiece ($T_{Hand\_Treatment\text{-}L\text{-}Workpiece}$) was calculated using the vibration measured on the hand-arm system ($A_{Hand\_Treatment\text{-}L}$) and that measured on the workpiece ($A_{Workpiece}$):

$$T_{Hand\_Treatment-L-Workpiece} = \frac{A_{Hand\_Treatment-L}}{A_{Workpiece}} = \frac{T_{Hand_{Treatment}-L-Handle}}{T_{Workpiece-Handle}}, \tag{3}$$

Hand_Treatment = BareHand and GlovedHand

L = hand dorsum, wrist, forearm, and upper arm

The location-specific glove vibration transmissibility with respect to the workpiece vibration ($T_{Glove\text{-}L\text{-}Workpiece}$) was calculated from:

$$T_{Glove-L-Workpiece} = \frac{T_{GlovedHand-L-Workpiece}}{T_{BareHand-L-Workpiece}}, \quad L = hand\ dorsum,\ wrist,\ forearm,\ and\ upper\ arm \tag{4}$$

2.4. Estimations of the location-specific effectiveness of the glove in the grinding of handheld workpieces

The location-specific effectiveness of the glove was estimated using a transfer function method, similar to that reported before (Dong et al., 2014). Specifically, the bare hand and gloved hand vibration accelerations at each location ($A_{BareHand\text{-}L}$, $A_{GloveHand\text{-}L}$) were estimated from the location-specific mean transmissibility spectra calculated using Eq. (2) and the workpiece mean vibration spectra ($A_{Workpiece\text{-}Actual}$) reported before and illustrated in Fig. 2(Chen et al., 2017), using the following formulas:

$$A_{BareHand-L} = \sqrt{\sum \left[T_{BareHand-L-Workpiece}(f_i) \bullet W(f_i) \bullet A_{Workpiece-Actual}(f_i)\right]^2}, \tag{5}$$

$$A_{GlovedHand-L} = \sqrt{\sum \left[T_{GlovedHand-L-Workpiece}(f_i) \bullet W(f_i) \bullet A_{Workpiece-Actual}(f_i)\right]^2}, \tag{6}$$

where W is the frequency weighting, and f_i is the center frequency in the 1/3 octave bands from 6.3 to 1250 Hz. Besides the standard frequency weighting (W_h) defined in ISO 5349-1 (2001). The unity weighting (W = 1.0 for unweighted acceleration) was also considered in the estimation of the location-specific glove effectiveness.

Then, the percent reduction of the vibration exposure (R_L) at each location on the hand-arm system was calculated from

$$R_L = \left(1 - \frac{A_{GlovedHand-L}}{A_{BareHand-L}}\right) * 100 \tag{7}$$

As further explained in the Discussion section (section 4.1), the transmissibility defined in Eq. (4) is equivalent to the glove vibration transmissibility at the hand contact surface. Therefore, it was used to estimate the glove's percent reduction of the vibration input to the hand interface ($R_{HandInterface}$) using the following formulas:

$$A_{Bare} = \sqrt{\sum \left[W(f_i) \bullet A_{Workpiece-Actual}(f_i)\right]^2}, \tag{8}$$

$$A_{Glove} = \sqrt{\sum \left[T_{Glove-L-Workpiece}(f_i) \bullet W(f_i) \bullet A_{Workpiece-Actual}(f_i)\right]^2}, \tag{9}$$

$$R_{HandInterface} = \left(1 - \frac{A_{Glove}}{A_{Bare}}\right) * 100 \quad (10)$$

2.5. Statistical analyses of vibration response functions/spectra

The effects of the influencing factors (glove, feed force, and grinding interface) on each type of vibration response function were analyzed to determine their statistical significance. A linear mixed-effects three-way ANOVA model was used to determine the significance of the variable factors on the dependent variables (system mechanical impedance, vibration transmissibility at each measuring location, and glove vibration transmissibility). Subject was treated as a random factor. The data for each function measured in the three trials for each test treatment were averaged and used in the statistical analyses. The three-way ANOVA model was performed for each frequency to determine the significance of the three factors and the two-way interactions between factors on the dependent variables. The mixed-effects three-way ANOVA model was performed with R statistical software (The R Foundation for Statistical Computing, version 3.5.3). Differences were considered significant at the $p < 0.05$ level.

3. Results

3.1. System impedance and workpiece response

As an example, Fig. 3(a) illustrates the Box & Whisker chart of the impedance data measured with the ten bare-handed subjects with an applied 30 N feed force on the R3 interface; the chart for the gloved-hand condition are illustrated in Fig. 3(b). The basic trends and features of the charts for other interfaces and 15 N feed force are similar to those shown in these figures. Fig. 3(c) and (d) illustrate the mean impedance spectra of the ten subjects for the six test treatments under 15 N and 30 N feed forces, respectively. Two resonant peaks can be identified in each of the mechanical impedance spectra. The first one is in the range of 20–25 Hz, and the second one is in the range of 315–630 Hz. The impedance values under the same feed force at each of the frequencies below 80 Hz were similar to each other. The major differences occurred in the second resonant frequency range and at higher frequencies. These observations were confirmed from the statistical analyses. Table 3 lists the ANOVA results on the impedance data. Reducing the feed force significantly reduced the overall impedance magnitude, especially in the second resonant frequency range. The only exception is at 63 Hz ($F_{1, 101} = 1.38$, $p = 0.24$). The use of the glove exhibited a statistically significant effect on the impedance, except at frequencies of 16, 400, 500, 1000, and 1250 Hz. Major significant 2-way interactions were found between interface and feed force at above 250 Hz, and between feed force and glove use at 12.5–16 Hz and 25–63 Hz.

Another set of statistical analysis focused on the second resonant peak of impedance. The results confirmed that reducing the interface stiffness (or increasing the interface rubber thickness) and reducing the feed force significantly reduced the second resonant peak frequency and magnitude ($F_{2, 101} \geq 92.84$, $p < 0.001$, and $F_{1, 101} \geq 295.55$, $p < 0.001$, for interface and feed force effects, respectively). The use of the glove significantly increased the peak frequency ($F_{1, 101} = 6.03$, $p = 0.02$), and marginally increased the peak magnitude

($F_{1, 101}$ = 3.71, p = 0.06). The only 2-way interaction were identified between interface and feed force ($F_{2, 101} \geq 9.72$, $p < 0.001$).

ANOVA tables similar to Table 3 were generated for all other dependent variables (vibration transmissibility spectra at different locations). Fig. 3(e) and (f) illustrate the ten-subjects mean spectra of the workpiece vibration transmissibility for the six test treatments under 15 N and 30 N feed forces, respectively. The first peak frequency occurred at 8 Hz for each of the three interfaces under both feed forces. The basic features of the workpiece transmissibility at frequencies above 100 Hz were similar to those of the system impedance, except that the second resonant frequency for each test treatment was lower than that in the system impedance ($F_{1, 216}$ = 157.93, $p < 0.001$). The feed force significantly affected the workpiece transmissibility ($F_{1, 101} \geq 4.14$, $p \leq 0.04$), with exceptions at 16, 25, 50, and 63 Hz ($F_{1, 101} \leq 3.19$, $p \geq 0.08$). Increasing the feed force increased the second resonant frequency and peak magnitude ($F_{1, 101} \geq 242.77$, $p < 0.001$). As also shown in Fig. 3(e) and (f), the interface conditions substantially affected the workpiece response in the second resonant frequency range and at higher frequencies (>250 Hz, $F_{2, 101} \geq 3.7$, $p \leq 0.03$). These observations also hold true for the glove effects (>315 Hz, $F_{1, 101} \geq 11.99$, $p < 0.001$). The specific glove effects on the workpiece resonant frequencies and peak values for all the test treatments are listed in Table 4, which indicate that the use of the glove marginally (<15%) increased the workpiece resonant frequency and peak value ($F_{1, 101} \geq 11.32$, $p < 0.001$).

3.2. Vibration transmissibility spectra on the hand-arm system

Fig. 4 illustrates the results measured on the hand dorsum. The hand dorsum measurements were largely different from the transmissibility spectra measured on the workpiece. The three spectra measured on the three interfaces under the same feed force and hand condition were similar to each other, as shown in Fig. 4(c) and (d). The statistical analyses also confirmed that the interface effect was generally not significant ($F_{2, 101} \leq 2.52$, $p \geq 0.09$). However, both feed force and hand condition (bare-hand and gloved-hand) had substantial effects on the vibration transmissibility measured on the hand dorsum ($F_{1, 101} \geq 4.43$, $p \leq 0.04$) in almost the entire frequency range (8–1000 Hz).

The spectra of the hand dorsum-specific glove vibration transmissibility on the three interfaces (R1, R2, R3) are illustrated in Fig. 4(e) for the 15 N feed force, and Fig. 4(f) for the 30 N feed force. In addition to the glove vibration transmissibility with respect to the workpiece vibration (R-Workpiece) calculated using Eq. (4), the glove vibration transmissibility with respect to handle vibration (R-Handle) calculated using Eq. (2) were also plotted in Fig. 4(e) and (f). They were very similar to each other, except some slight differences at some frequencies. This held true for the glove vibration transmissibility spectra at other locations on the hand-arm system. To simplify the following presentations, the glove vibration transmissibility spectra at these locations with respect to handle were not presented, and those with respect to the workpiece were used to describe the basic characteristics and influencing factors of the location-specific glove vibration transmissibility.

As expected, the hand dorsum-specific glove transmissibility generally decreased with the increase in frequency. Although there were some differences among the spectra for the three interfaces, as shown in Fig. 4 (e) and (f), the effect of the interface conditions on the glove vibration transmissibility was generally not statistically significant ($F_{2, 45} \le 2.96$, $p \ge 0.06$), except at 500 and 1250 Hz ($F_{2, 45} \ge 3.29$, $p \le 0.05$). Surprisingly, this also held true for the effect of the feed force, except that increasing the feed force significantly reduced the glove vibration transmissibility at some frequencies (40, 80, 100, 1000, 1250 Hz) ($F_{1, 45} \ge 4.23$, $p \le 0.05$).

Figs. 5–7 illustrate the results measured at the wrist, forearm, and upper arm, respectively. The vibration transmissibility on the hand-arm system generally reduced with the increase in the distance from the hand contact surface ($F_{2, 331} \ge 38.70$, $p < 0.001$). It was close to zero at the wrist at frequencies above 100 Hz, on the forearm at frequencies above 50 Hz, and on the upper arm at frequencies above 40 Hz. Statistical analyses were performed on the frequencies below the above identified frequencies at the three locations, where the transmissibility values were not close to zero. Similar to those observed in the transmissibility spectra measured on the hand dorsum, increasing the feed force generally increased the vibration transmissibility at each of the three locations on the hand-arm system ($F_{1, 101} \ge 17.30$, $p < 0.001$). The interface conditions generally had no significant effect on the transmissibility ($F_{2, 101} \le 2.74$, $p \ge 0.07$), with exceptions for forearm at 10–16 Hz ($F_{2, 101} \ge 3.26$, $p < 0.04$).

The effect of the glove on the transmissibility at wrist and forearm were generally significant. The specific affected frequency ranges for each location were clearly reflected in the location-specific glove transmissibility spectra shown in Fig. 5(e and f), 6 (e, f) and 7 (e, f). Surprisingly, although the vibration transmissibility was close to zero at frequencies above 100 Hz, the basic trends and features of the glove vibration transmissibility spectra at each location for the three interfaces in this frequency range remained similar. Similar to those observed in the hand dorsum-specific glove vibration transmissibility, increasing the feed force reduced the glove vibration transmissibility in a certain frequency range (100–200 Hz for the wrist; 400–800 Hz for the forearm; 400–800 Hz for the upper arm) ($F_{1, 101} \ge 6.36$, $p \le 0.02$), but the feed force did not significantly affect the glove vibration transmissibility in the other frequency ranges. The interface conditions had no significant effect on the glove vibration transmissibility at frequencies between 12.5 and 315 Hz ($F_{2, 101} \le 2.50$, $p \ge 0.09$). Statistically significant effects of interface condition were observed outside this middle frequency range.

The spectra shown in Fig. 4(e and f), 5(e, f), 6(e, f), and 7 (e, f) indicate that the glove vibration transmissibility determined using the on-the-hand method was generally location-specific. To clearly identify their similarities and differences, the spectra under the 30 N feed force for the four locations (hand dorsum, wrist, forearm, and upper arm) are plotted in Fig. 8, together with their average spectrum (mean of the four system locations), and the vibration transmissibility spectra of the same glove directly measured at the glove-fingers interface (Finger interface, under the 15 N grip force) and glove-palm interface (Palm interface, under the 30 N grip and 50 N push force) using adapter methods reported from previous studies (Xu et al., 2019). The general trends of the spectra derived from the vibration data measured on the hand dorsum, forearm, and upper arm at frequencies below 500 Hz were similar to each other. Their basic trends were also similar to those of the spectrum measured at the palm of the hand. However, there were large differences among their magnitudes. They were also largely different from the spectrum measured at the fingers and the spectrum derived from the vibration data measured at the wrist.

3.3. Estimated effectiveness of the glove in grinding operations

The vibration transmissibility spectra measured on the hand-arm system shown in Figs. 4–7(c, d) can be divided into two groups: the spectra measured with the glove and those measured with bare hand. The mean of the three interface-specific spectra in each group was used to represent the location-specific vibration transmissibility with or without wearing the VR glove. The two mean spectra were used to estimate the vibration reduction effectiveness of the glove using the method expressed in Eqs. (5)–(7). The estimated results for the four locations (hand dorsum, wrist, forearm, and upper arm) are listed in Table 5.

As explained in the Discussion section (section 4.1), the glove vibration transmissibility spectra for the four locations calculated using Eq. (4) are likely to be primarily associated with the vibration transmitted to the palm of the hand. Therefore, their average spectrum (Mean of the four system locations in Fig. 8) was used to estimate the overall effectiveness of the glove for reducing the vibration input to the palm of the hand using the method expressed in Eqs. 8–10. The estimated results (Palm Contact) are also listed in Table 5, as the palm contact surface can be considered as a special location on the hand-arm system.

The results listed in Table 5 suggest that the glove could reduce more vibration transmitted to the palm of the hand (Palm contact) than that listed in Table 1 in the grinding processes, in terms of both unweighted acceleration ($\mathbf{A_u}$) and weighted acceleration ($\mathbf{A_{wh}}$). The results also clearly indicate that the effectiveness of the glove for reducing the vibration on the hand-arm system is location-specific. The glove could reduce a large percentage of the vibration transmitted to the hand dorsum. It could also reduce some vibration transmitted to the wrist. Increasing the feed force from 15 N to 30 N could increase the glove effectiveness in some cases. However, the glove could not substantially reduce the vibrations at the forearm or upper arm, but it could slightly amplify the vibrations (<10%) at these locations in some cases.

4. Discussion

4.1. Interpretations and implications of the glove vibration transmissibility determined using the on-the-hand method

Theoretically, the vibration transmission from the handle to a gloved hand-arm system can be considered as two sequential events or processes: the vibration transmission (i) through the glove or from the handle to the glove-hand interface; and (ii) from the interface to a specific location on the hand-arm system. Therefore, the vibration transmissibility on the gloved hand-arm system with respect to the workpiece vibration ($T_{GlovedHand\text{-}L\text{-}Workpiece}$) can be expressed as the vibration transmissibility from the workpiece to the glove-hand interface ($T_{GlovedHand\text{-}Interface\text{-}Workpiece}$) multiplied by the vibration transmissibility from the interface to the hand-arm system ($T_{GlovedHand\text{-}L\text{-}Interface}$). Then, Eq. (4) can be written as follows:

$$T_{Glove-L-Workpiece} = \frac{T_{GlovedHand-L-Workpiece}}{T_{BareHand-L-Workpiece}} = \frac{T_{GlovedHand-Interface-Workpiece} \times T_{GlovedHand-L-Interface}}{T_{BareHand-L-Workpiece}} \quad (11)$$

If the use of the glove does not change the vibration biodynamic properties of the hand-arm system, the vibration transmissibility from the glove-hand interface to the hand-arm system should be similar to that measured in the bare hand test, or

$$T_{GlovedHand-L-Interface} \approx T_{BareHand-L-Workpiece} \quad (12)$$

Then, Eq. (12) can be simplified as follows:

$$T_{Glove-L-Workpiece} \approx T_{GlovedHand-Interface-Workpiece} \quad (13)$$

This equation means that, under the above-described ideal conditions, the glove vibration transmissibility spectra determined using the on-the-hand methods with the vibrations measured at different locations on the hand-arm system would be similar to each other; they would also be similar to the glove vibration transmissibility spectrum determined using a to-the-hand method, which measures the glove vibration transmissibility at the glove-hand interface using an adapter method (ISO 10819, 2013). Consistent with this theory, the basic trends and features of the glove vibration transmissibility spectra determined using the vibrations measured at the hand dorsum, forearm, and upper arm were similar to one another, as shown in Fig. 8. They also exhibit some similarities to those of the spectrum measured at the palm of the hand. These observations suggest that it is reasonable to use the average spectrum of those determined from the vibrations measured at the hand dorsum, wrist, forearm, and upper arm to represent the general glove vibration transmissibility at the palm of the hand. The consistency with the theoretical prediction also suggests that the on-the-hand method proposed in this study is acceptable for the testing and evaluation of VR gloves.

As expected, there were some large differences among the transmissibility spectra at different locations determined using the on-the-hand methods, as shown in Fig. 8. This is primarily because the vibration responses of a gloved hand-arm system may be different from those of a bare hand-arm system for the following reasons: (i) the glove may alter the hand contact force and pressure distribution, the postures of the hand and wrist, and the constraints and damping on the hand, which may change not only the biodynamic properties of the hand-arm system but also the specific hand location where the vibration inputs to the system; (ii) the hand-arm system is not a linear system; the glove-induced change in the vibration magnitude could also affect the vibration responses of the hand-arm system; and (iii) the measurement technologies may also bring about some uncertainties or errors. For example, the mass of the adapter and accelerometer and its fastening structure may change local biodynamics and affect the measured data (Griffin et al., 1982). As shown in Figs. 5–7, little vibration was transmitted to the wrist, forearm, and upper arm in the high-frequency range; a small perturbation in the measured data could result in a large error in the resulting glove vibration transmissibility, which suggests that the spectra at frequencies above 500 Hz may not be reliable. Some glove materials could overlap or come in contact with the adapter or accelerometer in the experiment, which could be one of the major reasons that the spectrum determined using the on-the-wrist method was substantially different from the other three spectra.

Also for these reasons, the average spectrum determined using the on-the-hand methods has some differences from that using the to-the-palm method, as shown in Fig. 8. This is also partially because the transmissibility measured at the palm of the hand using an adapter may not be fully representative of the overall glove transmissibility on the entire palm-glove interface (Dong et al., 2005). The adapter itself may also bring about some measurement errors because it may change the interface properties. Despite these differences, the effectiveness of the glove estimated using the average spectrum (see Table 5, Palm Contact) was comparable with that of the same glove estimated using the spectrum measured at the palm (see Table 1, Glove 1). These observations suggest that the basic cushioning mechanisms of the VR glove play a major role in determining the effectiveness of the glove for reducing the vibration transmitted to the palm of the hand.

4.2. The effects of grinding interface conditions and glove on workpiece responses and related glove vibration transmissibility

The cushioning mechanism of a VR glove is the primary design feature to reduce the hand contact stiffness between the workpiece and the hand. However, the reduced contact stiffness also reduces the constraints on the workpiece applied by the hands. As a result, the use of VR gloves may increase the workpiece vibration response magnitude along with its resonant frequency. The results shown in Fig. 3 and Table 3 support this hypothesis. However, the results shown in Fig. 4(e and f) do not support the further hypothesis: the increased workpiece response should reduce the vibration mitigation function of the gloves, but the changed workpiece responses did not significantly affect the glove vibration transmissibility spectra. This may be explained by the following observations: (1) this undesired glove effect primarily increases the vibration responses of the workpiece in its major resonant frequency range and at higher frequencies, as shown in Fig. 3(e and f); (2) the resonant frequencies of the workpiece on the interfaces simulated in this study were in the high-frequency range (>250 Hz), as also shown in Fig. 3(e and f); because the VR glove can effectively attenuate such high-frequency vibration, the significance of the increased workpiece response may be substantially reduced in the high-frequency range. These explanations suggest that the VR glove-induced increase in the workpiece vibration response should not be of concern in the use of VR gloves when the workpiece resonant frequency is comparable or higher than those observed in the current study.

4.3. The effect of feed force on the glove vibration transmissibility

Increasing the feed force significantly increased the vibration transmissibility on the hand-arm system both with and without wearing the glove, as shown in Figs. 4–7. This is because the increased feed force must increase the interface stiffness, the contact stiffness between the hand and workpiece, and the stiffness in the hand-arm system, which explain why there was a significant interface-force interaction on the mechanical impedance in the second resonant frequency range, as shown in Table 3. However, increasing the feed force did not significantly increase the glove vibration transmissibility; instead, it significantly reduced the transmissibility at some frequencies. A similar phenomenon was observed in a reported study (Md Rezali and Griffin, 2018). This is because increasing the feed force increases not only the glove stiffness that increases the glove transmissibility but also the apparent mass or mechanical impedance of the hand-arm system that reduces the glove transmissibility (Dong et al., 2009). If these two opposite effects mostly cancel each other, the feed force effect may become negligible. In addition, increasing the feed force also increases the major resonant frequency of the workpiece or the system. The glove may become more effective at the increased resonant frequency. These observations may explain why the predicted vibration reductions for 15 N and 30 N listed in Table 5 in most cases are similar to each other for each location on the hand-arm system.

4.4. Location-specific effectiveness of VR gloves

The results listed in Table 5 suggest that the effectiveness of VR gloves generally decreases with the increase in distance from the hand. This is partially because the glove vibration transmissibility generally decreases with the increase in frequency, as shown in Figs. 4–7. This is also partially because the fine grinding of handheld workpieces generates large high-frequency vibration components (Chen et al., 2017), as shown in Fig. 2. Because little vibration at frequencies above 50 Hz can be effectively transmitted to the forearm and upper arm, as shown in Figs. 6 and 7, VR gloves cannot attenuate much of the vibration transmitted to these locations. Therefore, VR gloves can primarily help attenuate the vibrations transmitted to the hand and wrist.

Finally, it should be noted that the percent reduction data listed in Table 5 should be used with caution. This is because the experiment was conducted on a 1-D test system, and the effectiveness of VR gloves may vary with vibration direction. The test conditions may also have some differences from those in the real grinding of workpieces. While the results obtained in this study are very encouraging, it should be worth conducting further experiments at workplaces to verify the findings of this laboratory experiment.

5. Conclusions

This study developed an on-the-hand method for evaluating the effectiveness of VR gloves for controlling the vibration exposures of workers performing the grinding of handheld workpieces. A theory was proposed to help understand the glove vibration transmissibility spectra determined using the vibrations measured at different locations on the hand-arm system, which also helped validate the proposed experimental method. The unique features of this method include automatically considering the glove cushioning function and other effects on the hand and arm vibration responses and having little interference or influence on the natural interactions among the workpiece, glove, and hands. Hence, this method may be applicable not only to laboratory experiments but also to the experiments at workplaces.

The results of this study confirm that VR glove effectiveness is generally location-specific. The use of VR gloves substantially reduced the vibrations transmitted to the palm of the hand and on the hand dorsum. It also reduced some vibration transmitted to the wrist. However, the use of VR gloves did not show much benefit for reducing the vibrations transmitted to the forearm and upper arm, because only low-frequency vibration can be transmitted to these locations; VR gloves cannot effectively reduce low-frequency vibration. This study also found that the use of VR gloves increased the resonant magnitude and frequency of the workpiece. Because the resonant frequencies considered in this study were in the high-frequency range (250 Hz), the increased resonance did not significantly affect the glove performance. Furthermore, the variations in grinding interface stiffness in its range considered in this study did not have a significant effect on the overall glove performance. Although increasing the feed force increased the workpiece resonant response magnitude along with the vibration transmissibility on the hand-arm system, the performance of the VR glove was not substantially affected. Instead, increasing the feed force from 15 N to 30 N increased the effectiveness of the VR glove in many cases. Based on these findings, this study concluded that the use of VR gloves should be helpful for controlling the vibration exposures of the workers performing the grinding of handheld workpieces, especially on a stiff grinding interface.

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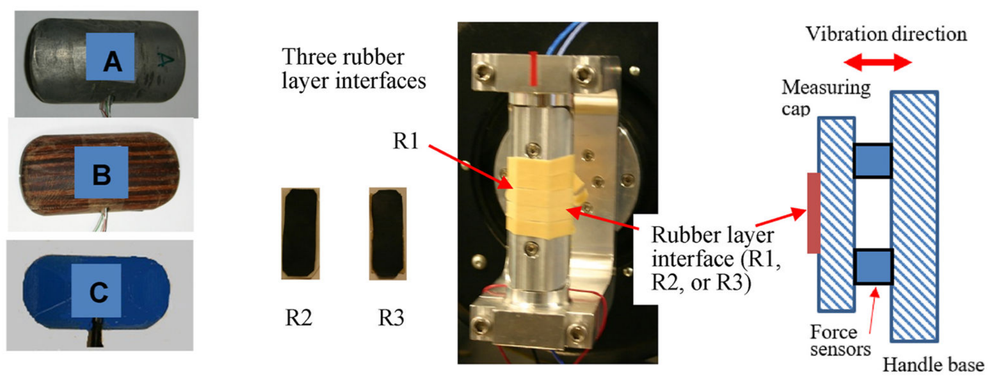
(a) A pictorial view of the simulation of a worker holding a workpiece (golf club head) and pushing against a simulated grinding interface



(b) Adapters for vibration measurements on wrist, forearm, and upper arms

(c) Instrumented handle and simulated interface (R1, R2, or R3)

Fig. 1.

Instrumentation and test setup: (a) a pictorial view of the simulation of a worker holding a workpiece (golf club head) with gloved hands and pushing against a simulated grinding interface; (b) three adapters (A, B, C) used to measure the vibrations at the wrist, the forearm, and upper arm; (c) instrumented handle and simulated grinding interface.

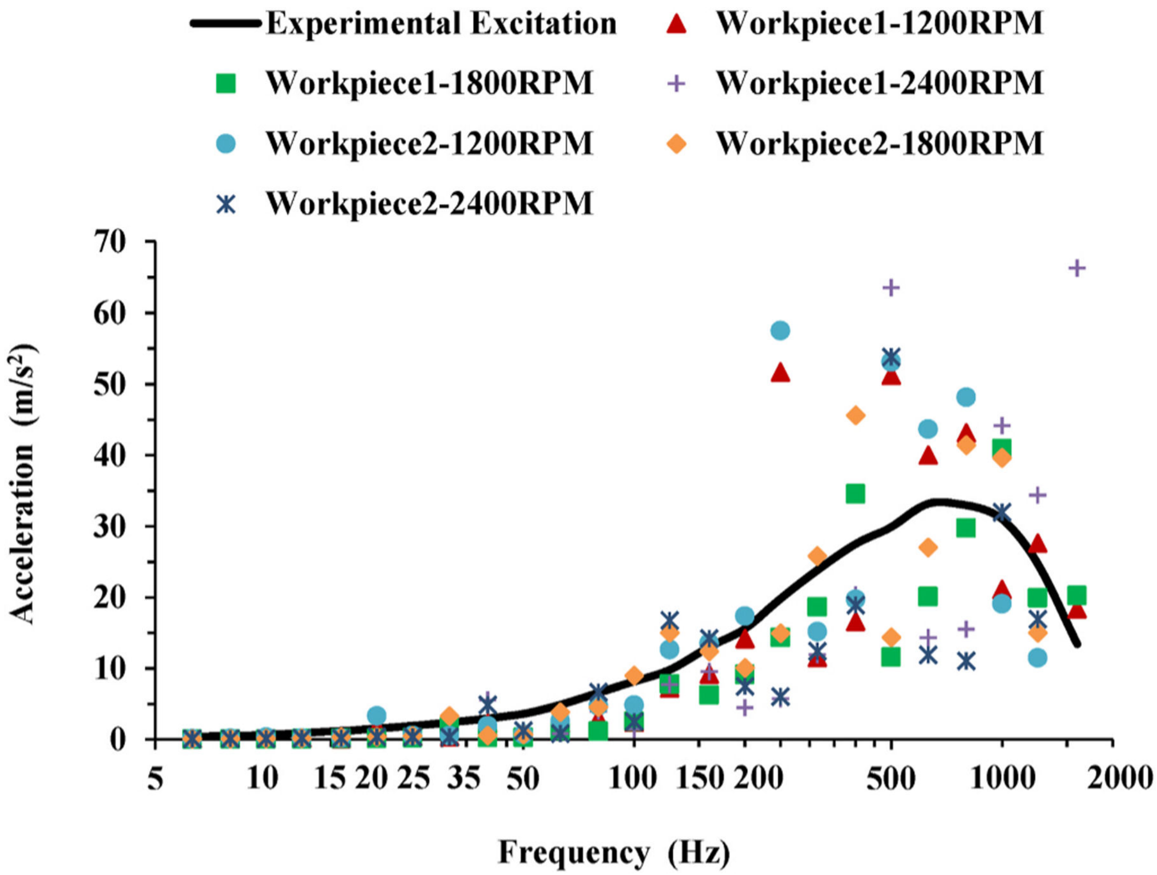


Fig. 2.

Comparisons of the vibration excitation spectrum used in the current study and the vibration spectra measured on handheld workpieces at different grinding wheel speeds (1200, 1800, and 2400 RPM) reported by Chen et al. (2017).

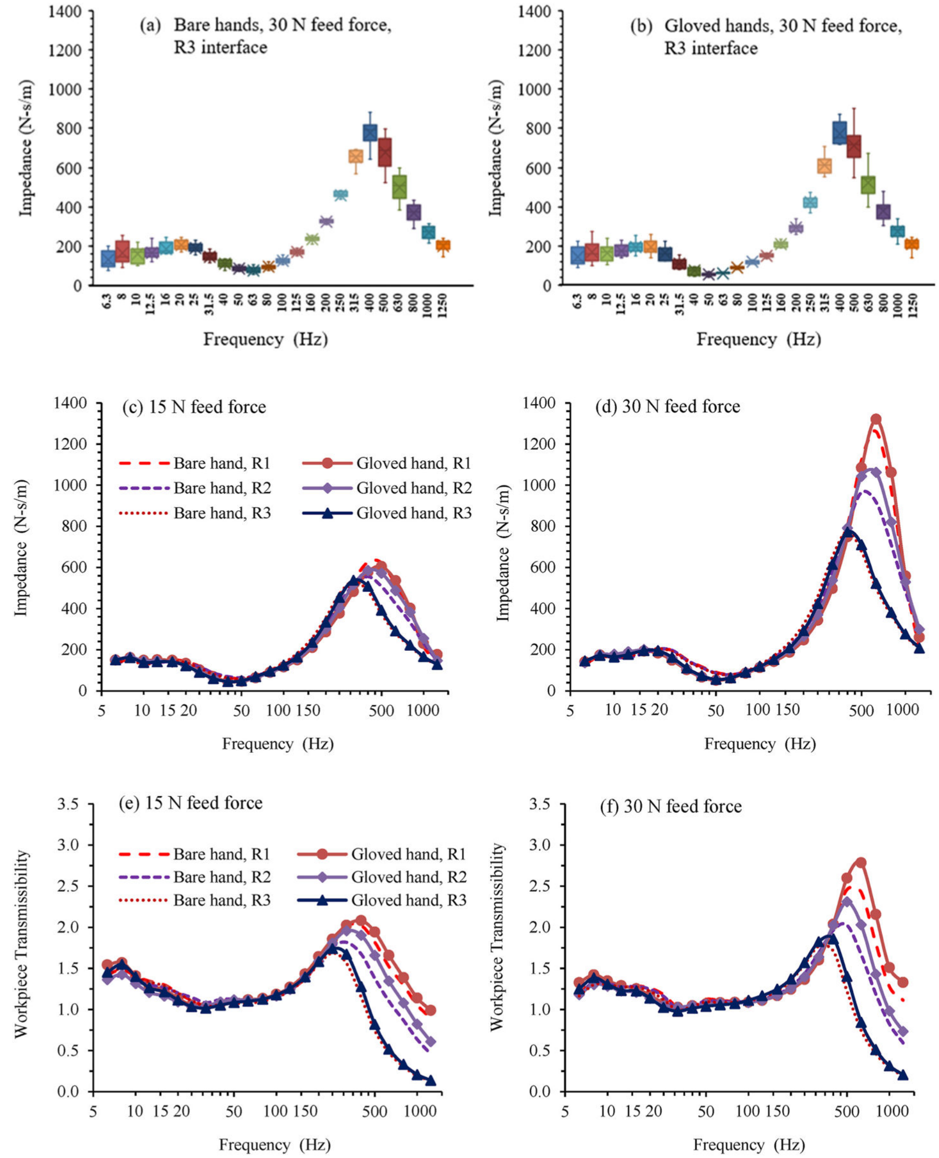


Fig. 3.

The mechanical impedance of the workpiece-hand-arm system and the vibration transmissibility of the workpiece: (a) the Box & Whisker chart of the impedance data measured with bare hands; (b) the Box & Whisker chart of the impedance data measured with gloved hands; (c) the mean impedance spectra measured in the six test treatments (3 interfaces × 2 hand conditions) under the 15 N feed force; (d) the mean impedance spectra measured in the six test treatments under the 30 N feed force; (e) the workpiece mean vibration transmissibility spectra measured in the six test treatments under the 15 N feed force; (f) the workpiece mean vibration transmissibility spectra measured in the six test treatments under the 30 N feed force.

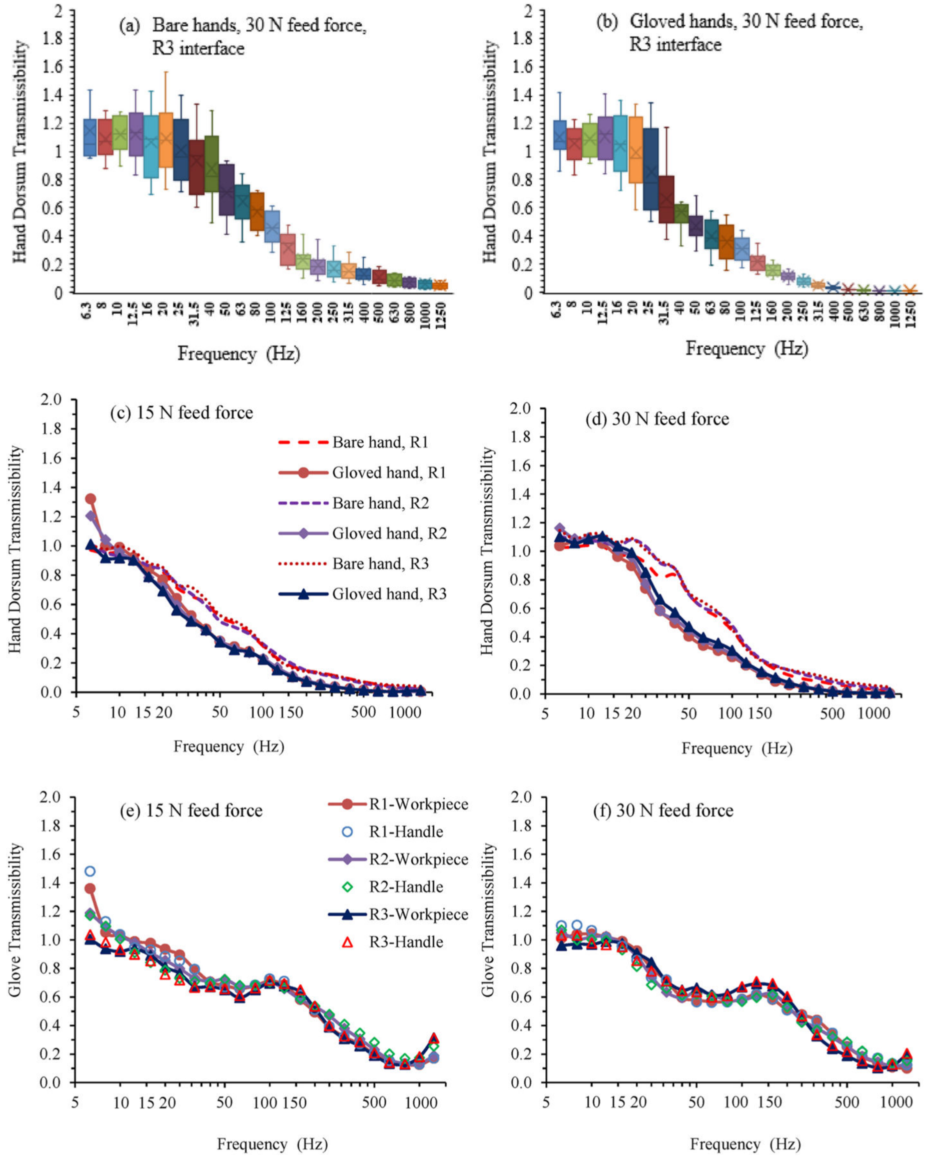


Fig. 4.

The vibration transmissibility measured on the hand dorsum with respect to workpiece and the related glove vibration transmissibility: (a) the Box & Whisker chart of the transmissibility data measured with bare hands; (b) the Box & Whisker chart of the transmissibility data measured with gloved hands; (c) the mean transmissibility spectra measured in the six test treatments (3 interfaces × 2 hand conditions) under the 15 N feed force; (d) the mean transmissibility spectra measured in the six test treatments under the 30 N feed force; (e) the mean glove vibration transmissibility spectra with respect to handle on each interface (R-Handle) and with respect to workpiece on each interface (R-Workpiece) for the 15 N feed force; (f) the mean glove vibration transmissibility spectra with respect to handle on each interface (R-Handle) and with respect to workpiece on each interface (R-Workpiece) for the 30 N feed force.

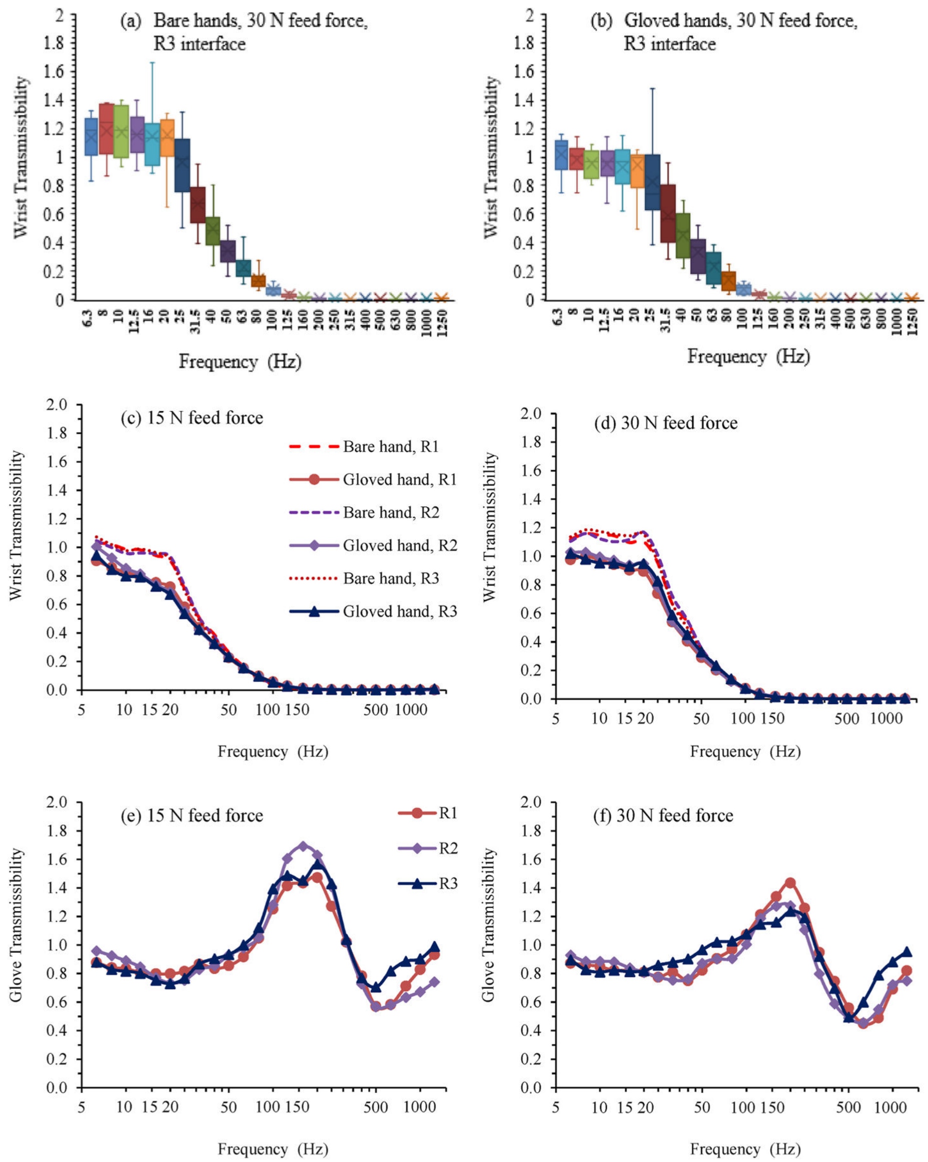


Fig. 5.

The vibration transmissibility measured at the wrist with respect to workpiece and the related glove vibration transmissibility: (a) the Box & Whisker chart of the transmissibility data measured with bare hands; (b) the Box & Whisker chart of the transmissibility data measured with gloved hands; (c) the mean transmissibility spectra measured in the six test treatments (3 interfaces × 2 hand conditions) under the 15 N feed force; (d) the mean transmissibility spectra measured in the six test treatments under the 30 N feed force; (e) the mean glove vibration transmissibility spectra on each of the three interfaces (R1, R2, R3) for the 15 N feed force; (f) the mean glove vibration transmissibility spectra on the three interfaces for the 30 N feed force.

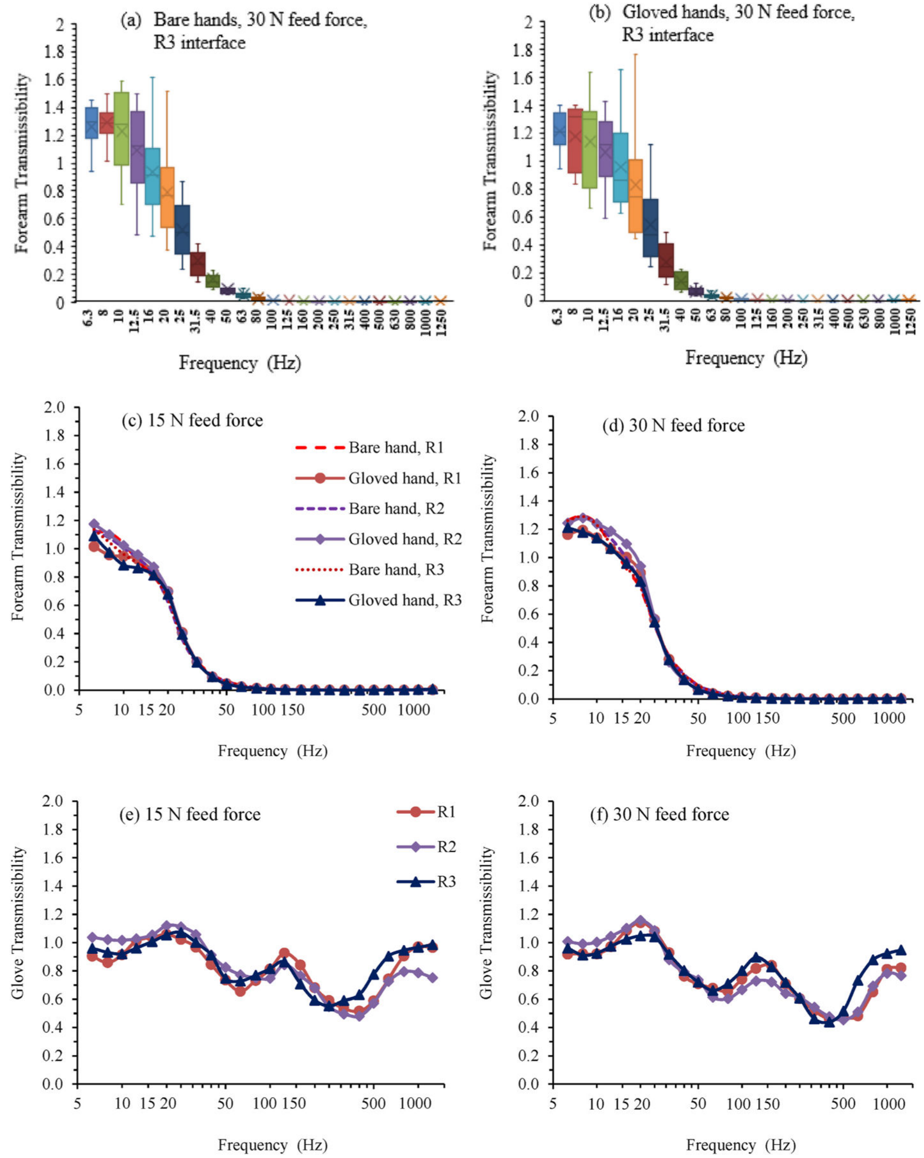


Fig. 6.

The vibration transmissibility measured on the forearm with respect to workpiece and the related glove vibration transmissibility: (a) the Box & Whisker chart of the transmissibility data measured with bare hands; (b) the Box & Whisker chart of the transmissibility data measured with gloved hands; (c) the mean transmissibility spectra measured in the six test treatments (3 interfaces × 2 hand conditions) under the 15 N feed force; (d) the mean transmissibility spectra measured in the six test treatments under the 30 N feed force; (e) the mean glove vibration transmissibility spectra on each of the three interfaces (R1, R2, R3) for the 15 N feed force; (f) the mean glove vibration transmissibility spectra on the three interfaces for the 30 N feed force.

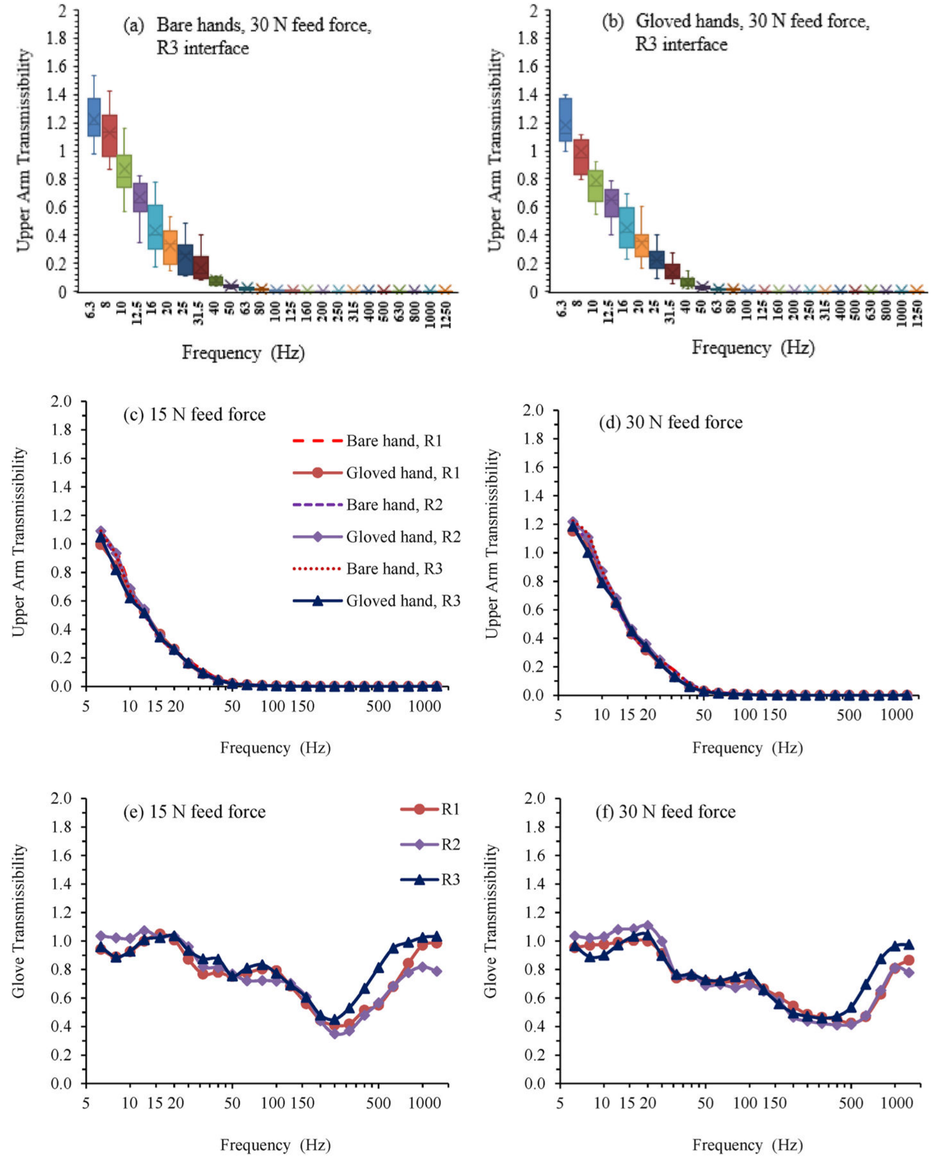


Fig. 7.

The vibration transmissibility measured on the upper arm with respect to workpiece and the related glove vibration transmissibility: (a) the Box & Whisker chart of the transmissibility data measured with bare hands; (b) the Box & Whisker chart of the transmissibility data measured with gloved hands; (c) the mean transmissibility spectra measured in the six test treatments (3 interfaces × 2 hand conditions) under the 15 N feed force; (d) the mean transmissibility spectra measured in the six test treatments under the 30 N feed force; (e) the mean glove vibration transmissibility spectra on each of the three interfaces (R1, R2, R3) for the 15 N feed force; (f) the mean glove vibration transmissibility spectra on the three interfaces for the 30 N feed force.

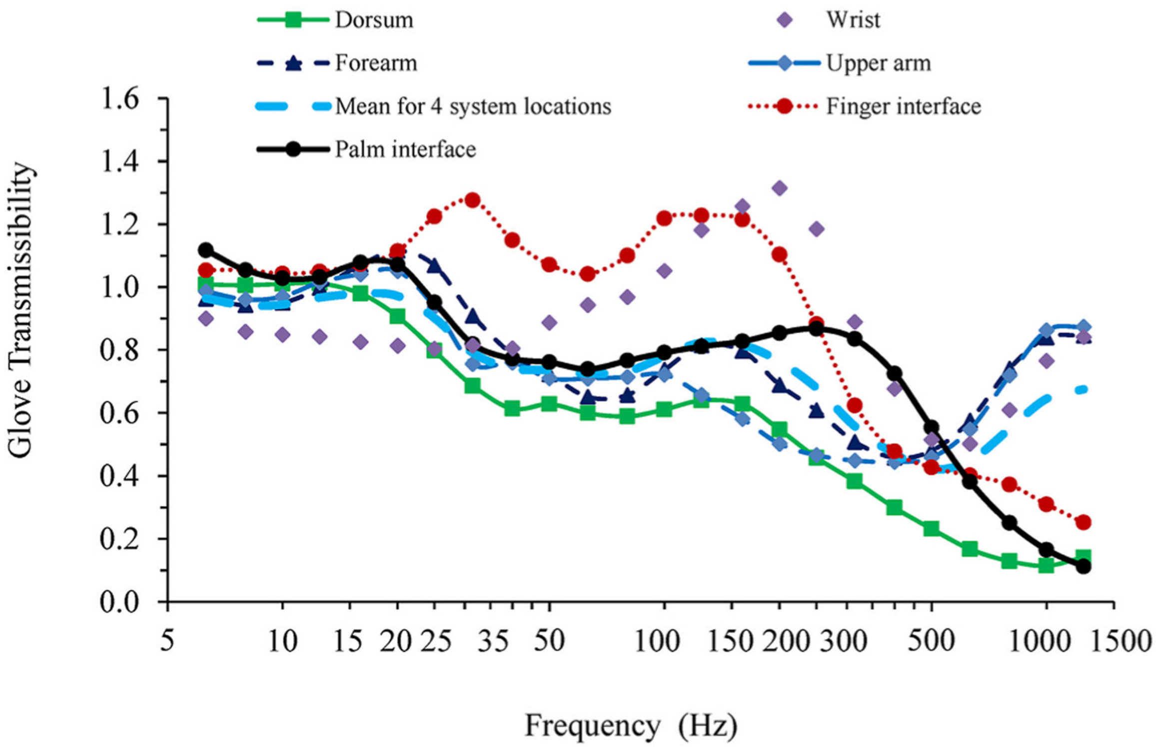


Fig. 8.

Comparisons of the location-specific glove vibration transmissibility spectra determined using the vibrations measured on hand dorsum, wrist, forearm, and upper arm under the 30 N feed force with the glove vibration transmissibility spectrum measured at the palm of the hand (palm interface) and the fingers (finger interface) under a 30 N grip and 50 N push force using adapter methods (Xu et al., 2019).

Table 1

Percent reduction of the vibration exposure in the grinding of two typical handheld workpieces (titanium-alloy golf club head and stainless-steel golf club head) when wearing three different AV gloves (Glove 1 - dipped neoprene glove; Glove 2 - gel-filled glove; Glove 3- air bubble glove), estimated using a transfer function method based on the average vibration transmissibility spectra of the gloves reported by Xu et al. (2019), and the average vibration spectra of handheld workpieces reported by Chen et al. (2017).

(a) Unweighted acceleration

Workpiece	Speed (RPM)	Unweighted Acceleration (m/s^2)	Percent Reduction at Palm (%)		
			Glove 1	Glove 2	Glove 3
Titanium-alloy golf club head	1200	103.7	41.5	36.7	41.6
	1800	73.8	49.9	45.5	50.7
	2400	91.9	53.3	50.8	57.3
Stainless-steel golf club head	1200	110.4	38.2	33.2	38.0
	1800	89.7	44.7	40.2	45.5
	2400	75.1	45.4	42.3	48.5

(b) ISO frequency-weighted acceleration

Workpiece	Speed (RPM)	W_h Weighted Acceleration (m/s^2)	Percent Reduction at Palm (%)		
			Glove 1	Glove 2	Glove 3
Titanium-alloy golf club head	1200	4.8	18.9	12.9	16.2
	1800	2.8	24.0	18.3	22.6
	2400	3.8	28.0	25.4	28.4
Stainless-steel golf club head	1200	6.0	14.6	9.1	12.4
	1800	4.6	22.3	17.0	20.8
	2400	4.2	24.1	19.7	23.1

(c) Alternative frequency-weighted acceleration

Workpiece	Speed (RPM)	Wp Weighted Acceleration (m/s^2)	Percent Reduction at Palm (%)		
			Glove 1	Glove 2	Glove 3
Titanium-alloy golf club head	1200	63.2	20.6	23.2	16.5
	1800	37.5	31.4	24.7	23.4
	2400	42.5	40.5	30.2	30.6
Stainless-steel golf club head	1200	71.5	17.6	20.9	14.7
	1800	51.1	24.9	19.4	19.6
	2400	42.5	20.6	17.1	18.4

W_h: The frequency weighting defined in ISO 5349–1 for assessing hand-transmitted vibration exposure.

Wp: The alternative frequency weighting defined in ISO/TR 18570: 2017 (2017) for assessing fingers-transmitted vibration exposure.

Table 2

Anthropometry data of the subjects in the experiment (hand length = tip of middle finger to crease at the wrist; hand circumference measured at the metacarpals; forearm volume was measured using a water-displacement method).

Subject	Height (cm)	Weight (kg)	Hand Length (mm)	Hand Circumference (mm)	Forearm Volume (ml)	Gender
1	157.5	97.5	190	201	1490	F
2	167.8	74.6	173	188	1328	F
3	158.5	51.1	174	177	967	F
4	169.6	61.5	175	178	980	F
5	164.0	54.0	181	190	995	F
6	181.5	78.1	187	218	1560	M
7	168.5	51.3	180	190	963	M
8	176.8	69.3	179	193	1180	M
9	177.5	136.7	193	231	2465	M
10	173.0	68.7	188	201	1310	M
Mean	169.5	74.3	182.0	196.7	1323.8	
SD	8.0	26.1	7.1	16.9	458.3	

Table 3

ANOVA table for 3-trial averaged impedance values measured from the 10 subjects under 12 different combinations of treatments for examining the effects of three operation factors: interface (3 simulated grinding interfaces: R1, R2, R3), force (2 levels of feed force: 15 N and 30 N), and glove (2 hand conditions: ungloved/bare hand and gloved hand). Differences were considered statistically significant at the $p < 0.05$ level.

Frequency (Hz)	Factors											
	Interface		Force		Glove		Interface × Force		Interface × Glove		Force × Glove	
	$F_{2,101}$	p	$F_{1,101}$	p	$F_{1,101}$	p	$F_{2,101}$	p	$F_{2,101}$	p	$F_{1,101}$	p
6.3	0.73	0.48	16.82	**0.00**	41.68	**0.00**	0.49	0.61	0.09	0.91	0.90	0.35
8	0.32	0.73	24.16	**0.00**	9.76	**0.00**	0.21	0.81	0.31	0.73	1.02	0.31
10	3.47	**0.03**	113.19	**0.00**	11.55	**0.00**	1.66	0.19	1.31	0.27	0.05	0.82
12.5	1.47	0.23	133.85	**0.00**	15.78	**0.00**	0.92	0.40	1.26	0.29	4.22	**0.04**
16	0.29	0.75	189.23	**0.00**	1.97	0.16	1.30	0.28	0.26	0.78	5.30	**0.02**
20	0.04	0.97	362.51	**0.00**	13.90	**0.00**	2.33	0.10	0.03	0.97	0.02	0.89
25	0.31	0.73	470.79	**0.00**	84.53	**0.00**	1.87	0.16	0.61	0.55	7.14	**0.01**
31.5	0.52	0.60	403.38	**0.00**	142.58	**0.00**	0.72	0.49	0.53	0.59	14.99	**0.00**
40	0.16	0.86	284.12	**0.00**	223.70	**0.00**	0.19	0.83	1.18	0.31	26.69	**0.00**
50	0.28	0.76	102.60	**0.00**	205.96	**0.00**	0.38	0.69	1.45	0.24	39.56	**0.00**
63	0.79	0.46	1.38	0.24	52.71	**0.00**	0.41	0.67	0.29	0.75	8.73	**0.00**
80	4.11	**0.02**	7.11	**0.01**	17.09	**0.00**	0.45	0.64	0.10	0.91	0.04	0.83
100	9.56	**0.00**	11.23	**0.00**	29.25	**0.00**	0.51	0.60	0.01	0.99	2.55	0.11
125	18.78	**0.00**	32.87	**0.00**	81.29	**0.00**	0.43	0.65	0.20	0.82	1.13	0.29
160	32.16	**0.00**	79.59	**0.00**	80.93	**0.00**	0.21	0.81	0.15	0.86	0.11	0.74
200	59.64	**0.00**	108.46	**0.00**	59.20	**0.00**	0.09	0.92	0.12	0.89	0.92	0.34
250	80.54	**0.00**	35.27	**0.00**	41.84	**0.00**	1.12	0.33	0.83	0.44	1.01	0.32
315	24.49	**0.00**	35.36	**0.00**	10.57	**0.00**	9.15	**0.00**	1.35	0.26	2.06	0.15
400	6.95	**0.00**	314.18	**0.00**	0.68	0.41	5.59	**0.00**	2.40	0.10	0.91	0.34
500	127.45	**0.00**	621.71	**0.00**	1.85	0.18	11.00	**0.00**	2.80	0.07	0.01	0.92
630	249.31	**0.00**	722.94	**0.00**	8.00	**0.01**	68.39	**0.00**	1.95	0.15	1.47	0.23
800	125.32	**0.00**	345.59	**0.00**	4.92	**0.03**	40.85	**0.00**	0.91	0.41	1.08	0.30
1000	45.71	**0.00**	211.93	**0.00**	1.37	0.24	16.28	**0.00**	0.27	0.76	0.11	0.74
1250	13.88	**0.00**	131.10	**0.00**	3.73	0.06	8.58	**0.00**	3.22	**0.04**	0.18	0.67

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Table 4

Effect of the VR glove on the resonant frequency and peak magnitude of the workpiece.

Simulated Interface	R1		R2		R3	
Feed force	**15 N**	**30 N**	**15 N**	**30 N**	**15 N**	**30 N**
Resonant frequency with bare hands (Hz)	364	570	312	469	261	346
Resonant frequency with gloved hands (Hz)	377	604	342	516	273	366
Percent difference (%)	3.7	6.0	9.5	9.9	4.8	5.7
Resonant peak acceleration with bare hands (m/s^2)	2.07	2.59	1.84	2.08	1.71	1.82
Resonant peak acceleration with gloved hands (m/s^2)	2.29	2.95	2.01	2.32	1.82	1.92
Percent difference (%)	10.9	14.0	9.3	11.5	6.4	5.7

Table 5

Predicted glove-induced reductions of the vibrations transmitted to the hand dorsum, wrist, forearm, and upper arm based on the transmissibility spectra measured with and without wearing the glove and the club head vibration spectra reported in a previous study (Chen et al., 2017).

Work-piece	Speed (RPM)	A_u (m/s^2)	Percent Reduction of Unweighted Acceleration (%)									
			Dorsum		Wrist		Forearm		Upper Arm		Palm Contact	
			15 N	30 N	15 N	30 N	15 N	30 N	15 N	30 N	15 N	30 N
Titanium-alloy golf club head	1200	103.7	56.6	54.4	18.8	16.8	−5.5	−7.6	0.5	−0.6	36.2	43.4
	1800	73.8	56.9	55.9	11.7	15.6	0.2	6.3	11.1	16.8	35.0	41.8
	2400	91.9	51.8	53.2	13.2	18.5	4.5	11.4	8.0	12.0	37.9	45.8
Stainless-steel golf club head	1200	110.4	51.2	49.2	21.5	17.1	−6.8	−10.0	−1.1	−3.1	36.0	43.2
	1800	89.7	47.2	48.3	9.2	13.7	−0.1	6.9	12.6	18.5	35.4	42.9
	2400	75.1	44.0	46.0	9.7	15.9	5.9	13.6	9.5	14.0	37.2	45.4
Work-piece	**Speed (RPM)**	**A_{wh} (m/s^2)**	**Percent Reduction of Weighted Acceleration (%)**									
			Dorsum		**Wrist**		**Forearm**		**Upper Arm**		**Palm Contact**	
			15 N	**30 N**	**15 N**	**30 N**	**15 N**	**30 N**	**15 N**	**30 N**	**15 N**	**30 N**
Titanium-alloy golf club head	1200	4.8	21.2	20.8	23.0	18.5	−6.3	−9.4	−0.5	−2.4	27.7	31.0
	1800	2.8	27.7	31.4	15.8	18.1	−0.9	2.8	7.0	10.8	27.5	33.7
	2400	3.8	27.6	34.8	15.7	18.9	0.7	3.2	3.8	4.8	25.8	33.3
Stainless-steel golf club head	1200	6.0	16.9	14.8	24.0	18.5	−6.9	−10.5	−1.4	−3.6	22.8	25.4
	1800	4.6	27.9	32.4	15.5	17.8	−1.6	2.6	8.0	12.5	21.5	28.8
	2400	4.2	29.4	36.2	14.8	18.5	1.5	4.9	4.6	6.0	19.5	27.8