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Vibration characteristics of golf club heads in their handheld grinding process and potential approaches for reducing the vibration exposure

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Abstract

To control vibration-induced white finger among workers performing the fine grinding of golf club heads, the aims of this study are to clarify the major vibration sources in the grinding process, to identify and understand the basic characteristics of the club head vibration, and to propose potential approaches for reducing the vibration exposure. The vibrations on two typical club heads and two belt grinding machines were measured at a workplace. A simulated test station was also constructed and used to help examine some influencing factors of the club head vibration. This study found that the club head vibration was the combination of the vibration transmitted from the grinding machines and that generated in the grinding process. As a result, any factor that affects the machine vibration, the grinding vibration, and/or the dynamic response of the club head can influence the vibration exposure of the fingers or hands holding the club head in the grinding process. The significant influencing factors identified in the study include testing subject, grinding machine, machine operation speed, drive wheel condition, club head model, mechanical constraints imposed on the club head during the grinding, and machine foot pad. These findings suggest that the vibration exposure can be controlled by reducing the grinding machine vibration, changing the workpiece dynamic properties, and mitigating the vibration transmission in its pathway. Many potential methods for the control are proposed and discussed.

Relevance to industry: Vibrations on handheld workpieces can be effectively transmitted to the hands, especially the fingers. As a result, a major component of the hand-arm vibration syndrome - vibration-induced white finger - has been observed among some workers performing

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the grinding and/or polishing tasks of the handheld workpieces such as golf club heads. The results of this study can be used to develop more effective methods and technologies to control the vibration exposure of these workers. This may help effectively control this occupational disease.

Keywords

Hand-arm vibration; Hand-transmitted vibration; Handheld workpiece vibration; Vibration-induced white finger; Golf club head

1. Introduction

Sanding, grinding, and polishing processes of handheld workpieces are important steps in the manufacture of some parts or components of machines, tools, sport equipment, and furniture. The fabrication of denture also requires performing dedicated sanding or grinding of fingers-held or handheld workpieces (Kaulbars, 2014). Such processes may generate significant vibrations of the workpieces, which may be effectively transmitted to the fingers or hands of the workers holding the workpieces. Prolonged, intensive exposure to such vibrations may cause hand-arm vibration syndrome (Griffin, 1990). A recent study reported that a significant prevalence (>12%) of vibration-induced white finger (VWF) (a major component of the syndrome) was found among workers performing the fine grinding and polishing of golf club heads (Chen et al., 2015). Effective interventions are required to stop such an occupational disease from spreading to more workers.

Important steps towards the objective intervention include clarifying the major sources of the workpiece vibrations, identifying and understanding their characteristics and influencing factors, and developing and applying appropriate methods and technologies to effectively reduce the vibration exposure. While the vibration sources and characteristics of many tools have been reported and some effective technologies have been developed to reduce the vibrations of tool handles, the vibration exposures of handheld workpieces have not been sufficiently studied. A literature search for this study found only scattered information on the vibrations of handheld workpieces (Ikeda et al., 1998; Kaulbars, 2014; Chen et al., 2015; Lin et al., 2015). While the frequency-weighted accelerations of some handheld workpieces were measured and reported in these studies, their vibration spectra were not measured or reported. Without such information, it is very difficult to clearly identify the vibration sources and influencing factors, characterize the vibrations of the handheld workpieces, and formulate or develop a set of effective methods to control the vibration exposure. As a result, it is unclear how to reduce the magnitudes of vibration from the grinding and polishing processes and how to minimize transmission of vibration to the hands of workers.

The objective of this study is to enhance the foundation for the further developments of effective methods and technologies to control the vibration exposure. Specifically, the vibration spectra of typical club heads are measured during their handheld grinding process at a workplace, together with the measurement of the vibration spectra on typical grinding machines. The machine and club head vibration spectra are used to identify and confirm the vibration sources. The club head vibration spectra are also used to calculate the frequency-weighted vibration spectra and the acceleration value defined in ISO 5349–1 (2001). The factors examined in this study include finger coupling force, grinding drive wheel condition, grinding machine foot pad, machine operation speed, vibration measurement method, etc. A simulated workstation of the grinding process is also constructed and used to help the examination. Based on the identified vibration sources, characteristics, influencing factors, and our understanding, a set of potential approaches for reducing the vibration exposure of the workers performing the grinding tasks of the club heads are proposed and discussed.

2. Methods

2.1. The nature of fine grinding and polishing processes for manufacturing golf club heads

Currently, the major manufacturing processes of a golf club head usually include casting, fine grinding, and final polishing. Fig. 1 shows an example of the fine grinding of a golf club head conducted at a typical workstation in a sport equipment manufacturer in Guangdong, China. Belt grinding machines are generally used in the grinding process. Each club head is held primarily by the fingers of both hands during the grinding or polishing process. Many of the grinding workers are paid based on the number of processed club heads and the workers are usually very productive. To make the grinding process efficient, they must quickly find the right location and orientation of the head surface to be ground and to apply appropriate push and grip forces for a certain time. The workers also often change the grinding location and orientation of the piece during the grinding process based on their observations, perceptions, and experience to achieve the desired result Some workers also quickly swing and move the club head around to achieve the desired grinding quality. A quick measurement of the workpiece dimensions before and/or after the grinding is also occasionally performed to assure the required dimensions. These operations require dexterity of the fingers. As anti-vibration gloves certified according to ISO 10819 (2013) may largely reduce the finger dexterity and increase the grip effort (Wimer et al., 2010), the workers doing the fine grinding do not wear such gloves but they wear regular full-finger working gloves. The gloves are used primarily to protect their fingers from burns by the workpiece heated during the grinding process and to reduce some vibration. In addition to wearing a pair of work gloves, many workers also wear a pair of soft cloth gloves on top of the work gloves for additional protection.

Fig. 2 shows the two types of belt grinding machines used in this study for the measurements of the machine vibration and the club head vibration. The machine operation speed is the rotational speed of the grinding drive wheel. There are three speed choices (1,200, 1,800, and 2400 revolutions per minute (RPM)) for the large-wheeled machine and two speed choices (1,800, 2800 RPM) for the small-wheeled machine. The grinding belt is replaced when it is worn out after grinding a certain number of the club heads. The drive wheel is also replaced when the rubber treads of the drive wheel is worn by the friction between the grinding belt and the rubber treads. The polishing process is usually performed after the grinding process is completed. The basic working conditions and hand-arm postures shown in Fig. 1 for the grinding process are similar to those observed in the polishing process. The vibration observed in the polishing process is usually lower than that in the grinding process. For these reasons, this study focused on the investigation of the grinding process. The experimental study was designed based on these features of the grinding tasks and the general working conditions.

2.2. Experiment I: examination of the methods for measuring the handheld club head vibration in their grinding process

The first experiment of this study was focused on the identification of a suitable method for the vibration measurement of the club heads in their handheld fine grinding process. Unlike the vibration measurement on tools specified in ISO 5349–2 (2001), the location and orientation for the measurement on a handheld workpiece are not specified in the standards. It also remains an issue how to attach an accelerometer on small workpieces for the measurement (Kaulbars, 2014). Four attachment approaches (screwing, gluing, using a hose clamp, or using a handheld adapter) are recommended in ISO 5349–2 (2001). The first three approaches, especially the clamping approach, are generally more reliable than the adapter approach for the vibration measurement on a tool handle, as their frequency response functions are closer to unit in the frequency range of concern (Moschioni et al., 2007; Ainsa et al., 2011). Unfortunately, the first three approaches are not generally suitable to measure the vibration on many handheld workpieces, as they may damage the workpieces or substantially interfere with the normal operational tasks. A non-contact technology such as a laser vibrometer is not applicable for the vibration measurement on the club head in the grinding process. The adapter approach seems a practical, convenient, and efficient choice for such measurement. A study has identified the basic requirements for the appropriate application of the adapter approach (Xu et al., 2014). However, it is unclear how this approach can be appropriately applied to measure the vibrations of the club heads during grinding and polishing processes. This issue was addressed in the first experiment of this study by comparing four accelerometer installation methods shown in Fig. 3. A stainless-steel golf club head with a hollow center was used in the test The screwing method or Method (a) shown in Fig. 3(a) is one of the methods recommended in the standard (ISO 5349–2, 2001). It was used as a reference to evaluate the other three methods shown in Fig. 3(b, c, d). For this purpose, one experienced worker participated in this experiment. Twenty trials were performed. Each trial lasted about 20 s. As also shown in Fig. 1, a portable data acquisition and analysis system (Svantek, SV106) was used to measure the frequency-weighted accelerations in three orthogonal directions (x, y, and z) according to ISO 5349–1 (2001).

The results presented in Section 3.4 suggest that the fingers-held adapter method or Method (b) is the best choice for the above-described working conditions. This is primarily because in the grinding process, the palm is not always kept in contact with the club head with Method (c) and the thumb could not hold the accelerometer with Method (d) with the same stability as the fingers did with Method (b). Therefore, Method (b) was used in the remaining experiments at the workplace.

2.3. Experiment II: the measurement of club head vibration at a workplace

The second experiment focused on the measurement of the frequency-weighted acceleration on the club head according to the standard method defined in ISO 5349–1 (2001). Along with measuring the acceleration, the probe/adapter shown in Fig. 3(b) used in this experiment is also equipped with a force sensor, which was also used to measure the finger coupling force (average value during each measurement period) normal to the contact surface of the club head. To explore the vibration exposure level of the workers using typical grinding stations, three experienced workers participated in the experiment. The testing workers were randomly selected from the experienced workers who had continuously worked on the grinding jobs for more than three years. The two typical grinding machines shown in Fig. 2 were used in the experiment The vibration on a typical model of titanium alloy club head was measured in the experiment. Before and during the experiment the workers were advised to conduct the grinding tasks using their regular technique as much as possible. Three trials were performed for the test on each machine. During each trial, three club heads were ground, which lasted between 8 and 20 s, depending on the amount of the grinding required for each of the three club heads and the skill and efficiency of each worker. The average value for each trial was recorded and used in the post analyses. To explore the vibration characteristics, the vibration spectra of the club head in the one-third octave bands were also measured in some trials of this experiment.

2.4. Experiment III: the measurements of the machine and club head vibration spectra

The third experiment was designed to examine the relationship between the machine vibration and the club head vibration. The vibration spectra on the two machines shown in Fig. 2 were measured with and without grinding. The vibrometer (Svantek, SV106) was also used in the measurement, which can directly output the vibration spectra in the one-third octave bands. For the purpose of this study, the spectra from 0.8 to 2000 Hz were recorded. In the measurement of the machine vibration, a tri-axial accelerometer was glued to a flat surface on a solid structure above the bearing of the drive wheel shaft on each machine. The specific location for the accelerometer installation on the large-wheeled machine is shown in Fig. 2(a). For the small-wheeled machine, the accelerometer was installed at the origin of the coordinate system shown in Fig. 2(b). Besides the glue, a rubber band was also applied to secure the accelerometer on each machine. The basic variables considered in the experiment included two models of club heads (titanium alloy and stainless steel) and the possible operation speeds on each machine. On the large-wheeled machine, two additional variables were considered: the two types of the machine foot pads (original plastic pad and new rubber pad) and two drive wheel conditions (normal or ordinary drive wheel and worn drive wheel shown in Fig. 4). In the free-run test, no grinding was conducted and the machine vibration spectra in the three orthogonal directions were measured after the machine was in a stable running condition. In the grinding test, the club head and machine vibration spectra in the one-third octave bands were simultaneously measured. For the purpose of this experiment, two experienced workers participated in the grinding experiment. Two trials were performed for each of the test treatments. The recording time for each trial was 10 s.

2.5. Experiment IV: experiments on a simulated test station

To avoid the effect of the human subjects on the vibration measurement, a simulated test station was constructed based on the large-wheeled machine, which is shown in Fig. 4. While no change was made on the grinding machine itself, the human hand-arm system was replaced by a grinding feed system. The feeding system was basically composed of a club head fixture and a pneumatic actuating device. While the head fixture can freely slide in a direction on a base fixed on a table, the actuator can translate the head on the fixture into contact with the grinding belt through a pushing beam; then, it applies a constant feed force on the club head during the grinding process. The feed force is measured using a force sensor installed at the interface between the pushing beam and the head-fixture and it is controlled by adjusting the pressure of the air supply to the actuator. Furthermore, to assure sufficient grinding material and consistent grinding surface geometry for each trial, a small block of the same material as the stainless-steel club head was welded on the grinding surface of the club head; the actual grinding surface was not on the club head but on the welded material. Because such a test station does not provide a close simulation of the hand-arm system, it may only be used to explore the effects of some influencing factors on the club head vibration. For this purpose, the screw method for the accelerometer installation shown in Fig. 3(c) was used to measure the club head vibration on the simulated test station.

As the fourth experiment, three more factors were considered, which included three motor speeds (1200, 1800, 2400 RPM), two drive wheel conditions (normal and worn out drive wheels shown in Fig. 4), and two types of machine base suspensions (ordinary plastic pad and new rubber pad). A constant push force of 20 N was applied during all the test treatments. Six trials were performed for each test treatment.

2.6. Statistical analyses

Whenever applicable, a general linear model for the analysis of variance (ANOVA) was used to determine the significance of the effects of test conditions on the vibration magnitude. Whenever necessary, independent sample *t*-tests were also performed to examine the significance of the vibration differences. Differences were considered significant at the $p <$ 0.05 level. Whenever useful, correlation analyses were also performed to confirm the relationship between two different measures.

3. Results

3.1. The vibration spectra of the golf club heads measured in the grinding test in experiment III

Fig. 5 shows examples of typical vibration spectra measured on the club head. As shown in Fig. 5(a), the vibration magnitude of the club head varied with the measurement direction in the coordinate system fixed on the probe or adapter. However, the general shapes or major peak frequencies in the three translational axes remained similar, especially in the major frequency range of concern (6.3–1250 Hz) for hand-arm vibration (ISO 5349–1, 2001). This was further confirmed from the correlation analysis of every set of the tri-axial spectra ($r =$ 0.79 to 0.97). Similarly, as shown in Fig. 5(b), the vibration magnitude varied with trials but that did not change the basic trends of the total vibration spectra. The spectra measured in different trials for the same subject were highly correlated ($r = 0.84$ to 1.00). As shown in Fig. 5(c, d), the vibration magnitude also varied with subjects but the spectra measured on the same machine with different subjects were also highly correlated ($r = 0.98$ to 1.00). These correlations suggest that the vector summation and averaging process will not change the basic features of the vibration spectra. For simplicity, the total vibration (vector sum) of the three axial vibrations is generally considered in the following analyses and presentations, if not specified.

Fig. 6 shows the vibration spectra of the two club heads (titanium alloy and stainless steel), together with their frequency-weighted spectra calculated using the standard weighting factors defined in ISO 5349–1 (2001). The vibration spectra measured on each club head while grinding generally varied with the operation speed and machine type. However, the basic trends and peak frequencies of the vibration spectra did not vary substantially with club head models. The first major peak frequency was always associated with the operation speed of the machine. For example, for the machine speed at 1200 RPM, the peak was at 20 Hz (= 1200 cycles/60 s), as shown in Fig. 6(a). For the remaining speeds (1800; 2400; and 2800 RPM), the first peak was at 31.5, 40, and 50 Hz, respectively, as shown in Fig. 6(b, c, e). The second and third major peaks were integer multiples of the first major peak frequency in many cases. For example, they were 40 Hz and 60 Hz (within 63 Hz one-third octave band) for the speed at 1200 RPM, as shown in Fig. 6(a), and 80 Hz and 120 Hz (within 125 Hz one-third octave band) for the speed at 2400 RPM, as shown in Fig. 6(c).

Below the first major peak frequency, the vibration was generally small (<0.3 m/s^2), as shown in Fig. 6. However, it was also observed that some low frequency components exceeded 0.5 m/s^2 if a worker quickly swung the club head during grinding, as shown in Fig. 5. As also shown in Figs. 5 and 6, there were many high-frequency components at frequencies above 250 Hz. Their peaks also varied with the machine operation speed.

Because the weighting factor below 63 Hz is greater than 0.256 with a peak (0.958) at 12.5 Hz and it becomes less than 0.0634 at frequencies above 250 Hz, the high frequency components are greatly suppressed and the weighted acceleration values are less than 0.15 m/s^2 at frequencies above 1250 Hz, as shown in Fig. 6. As a result, the first major peak usually constitutes the highest component of a weighted spectrum. The majority of the remaining weighted peaks are also in the middle frequency range (20–250 Hz). These indicate that the frequency-weighted acceleration value required for assessing the risk of the vibration exposure depends primarily on the vibration components in the middle frequency range.

3.2. The vibration spectra measured in experiment III without grinding (machine free-run test)

Fig. 7 shows the vibration spectra measured in the free-run tests of the machines. As shown in Fig. 7(a, b), the vibration spectra in the three directions on each machine are correlated to each other in the major frequency range of concern ($r > 0.90$, $p < 0.001$). However, the vibration measured in the x direction or along the axial direction of the shaft was generally lower than those measured in the other two directions on both machines ($p < 0.001$). This indicates that the major vibration of the machines was in the y-z plane or the wheel rotation plane.

As also shown in Fig. 7(a, b), the basic trends of the vibration spectra measured on the two machines are similar. To demonstrate the effect of the operation speed on the machine vibration, Fig. 7(c, d, e, and f) shows the total vibration spectra of the large-wheeled machine measured at the three speeds (1,200, 1,800, and 2400 RPM) in four test treatments (2 wheel conditions × 2 machine foot pads). The vibration magnitudes were usually very small (<0.1 m/s^2) before the first major peak frequency (≥ 20 Hz) but they generally increased with frequency. As observed in the vibration spectra of the club heads, the first major peak frequency was always correlated with the machine operation speed. The remaining major peak frequencies were also mostly integer multiples of the first peak frequency, which is clearer than that observed in the club head vibration spectra shown in Fig. 6. While increasing the operation speed did not always increase the club head vibration, increasing the speed always substantially increased the first peak magnitude of the machine vibration ($p < 0.001$).

Fig. 8(a) shows that the new foot pad significantly increased the peak values in the middle frequency range (6.3–250 Hz) but generally reduced the peaks at frequencies above 250 Hz ($p < 0.001$), except that at 800 Hz. Fig. 8(b) shows the effect of the wheel condition on the machine vibration. The spectrum measured with the worn wheel is only marginally different from that measured with the normal wheel and the effect is not consistent across the frequencies.

3.3. The relationship between the vibrations of the club head and machine

Fig. 9 shows the comparisons of the club head and machine vibration spectra simultaneously measured on the machines in Experiment III, together with those measured in the machine free-run tests. As shown in Fig. 9(a, b, c), there were generally few differences between the vibration spectra measured with and without performing any grinding on the large-wheeled machine. This also holds true for the small-wheeled machine at frequencies equal to or less than 63 Hz for 1800 RPM and at frequencies less than 125 Hz for 2800 RPM, as shown in Fig. 9(d, e). At higher frequencies, however, the grinding substantially affected the vibration of the small-wheeled machine.

As also shown in Fig. 9, both the machine vibration and club head vibration generally increase with the increase in frequency. The strongest correlation was at the first major peak frequency associated with the machine operation speed. High correlations were also observed for almost all the peaks in the middle frequency range (20–250 Hz) or the entire frequency range, as shown in Fig. 10. However, the mean vibration spectra shown in Fig. 9 indicate that the club head vibration was not well correlated with the machine vibration at some frequencies, especially in the very low (<6.3 Hz) and high frequency range (>250 Hz), as shown in Figs. 9 and 10(b).

3.4. The frequency-weighted total vibration value (a_{hv}) measured at the workplace in experiment I, II, and III

Table 1 lists the results from Experiment I for examining the measurement methods. The average value measured with the fingers-held adapter method (2.34 m/s^2) is not significantly different from the reference average value (2.42 m/s^2) measured with the accelerometer screwed on the club head (Method a) ($p = 0.293$). However, the values measured with other methods are significantly different from the reference value ($p < 0.001$). These observations confirm that the fingers-held adapter method is a better choice than the thumb-held or palm-held methods for measuring the club head vibration.

The average coupling force measured with the adapter was recorded every second, together with the total vibration value (a_{hv}) in Experiment II. The force value was well correlated with the vibration value in some trials. However, the correlation was not observed in the vast majority of the trials. As a result, the overall values of the coupling force were not well correlated with the total vibration values, as indicated in the data listed in Table 2.

Table 2 also lists the total vibration values measured in Experiment II. While the intra-subject variations of the measured vibrations were generally less than 15%, the inter-subject variation was very large (25%). Although the three workers performed exactly the same tasks, the results listed in the table suggest that their vibration exposures were significantly different ($p < 0.001$). The club head vibration measured on the large-wheeled machine was less than that measured on the small-wheeled machine ($p < 0.001$).

Table 3 lists the weighted acceleration values of the club heads calculated using the spectra (from 6.3 to 1250 Hz) shown in Fig. 9, which were measured in Experiment III. Consistent with the data measured in Experiment II (Table 2), the weighted acceleration measured on the small-wheeled machine was larger than that measured on the large-wheeled machine ($p < 0.02$). The weighted vibration measured on the stainless steel head was generally larger than that measured on the titanium alloy head ($p = 0.002$). The weighted vibration of the club heads generally reduced with the increase in the speed ($p < 0.05$), except the comparison of the data for Titanium club head measured at 1800 RPM and 2400 RPM.

3.5. The results measured on the simulated test station in experiment IV

Table 4 lists the weighted acceleration values of the stainless steel club head measured on the simulated test station in the fourth experiment Contradicting that observed in the third experiment (Table 3), increasing the machine speed increased the grinding vibration ($p < 0.001$). The vibration measured with a normal drive wheel was less than that with a worn drive wheel ($p < 0.001$). The base suspension condition was also a significant factor of the grinding vibration ($p < 0.001$). The vibration values of the stainless steel club head measured on the simulated test station are much less than those measured in the subject test at the workplace (Table 3) ($p < 0.001$).

4. Discussions

The experimental results and observations provide some useful information for identifying and understanding the basic vibration sources and characteristics of golf club head grinding. The results and observations form a basis for proposing and discussing vibration control approaches.

4.1. Vibration sources on a grinding machine

According to well-established knowledge (Bate, 1988), each belt grinding machine equipped with an electric motor has two types of vibrations: magnetic and mechanical vibrations. The magnetic vibration results from the non-uniformly distributed magnetic field in the electric motor and its major frequencies are associated with the line frequency (f_{Line}) of the electric power. The mechanical vibration results from the unbalanced mass of the rotational parts, misalignment and bending of the rotor shaft, and bearing defect or wear of the machine. Its major frequencies are associated with the operation speed (f_{Speed} = RPM/60) of the machine.

The line frequency at the experimental site is 50 Hz. Therefore, the major magnetic vibration should be around 50 Hz ($1*f_L$), 100 Hz ($2*f_L$). and so on (integer**f_L) Coincidentiy, the vibration spectra of the small-wheeled machine exhibit a peak at 50 Hz and another one at 100 Hz, as shown in Fig. 9(e). However, the correlation alone is not sufficient to prove the existence of substantial magnetic vibration, because the mechanical vibration can also occur at these frequencies. The motor speed for this case was 2800 RPM and its $f_{Speed} \approx 47$ Hz. The corresponding mechanical vibration can be observed as 50 Hz and 100 Hz (Bate, 1988), which are in the one-third octave bands for 50 Hz ($1*f_{Speed}$) and 100 Hz ($2*f_{Speed}$), respectively. In such a case, it is difficult to clearly differentiate magnetic and mechanical vibrations. This is also because the mechanical vibration can affect the geometrical gaps in the motion and the magnetic field such that additional magnetic vibration may be generated. There is no obvious vibration peak at the line frequency (50 Hz) in the vibration spectra measured on the two machines at other speeds, as shown in Figs. 5 and 9. A small peak can be observed at 100 Hz ($2*f_L$) in the machine vibration spectra at 1800 RPM ($f_{Speed} = 30$ Hz), as shown in Fig. 9(b,d). This evidence is also insufficient to confirm the existence of the magnetic vibration, as a possible mechanical vibration frequency ($3*f_{Speed} = 90$ Hz) is on the boundary of the one-third octave band for 100 Hz. The lack of obvious magnetic vibration may be because substantial magnetic vibration usually occurs only when the motor is poorly designed or manufactured or it has significant defects or damage (Bate, 1988).

The machine vibration spectra shown in Figs. 7–10 indicate that the major vibration peaks are in the middle frequency range (20–250 Hz) and they are mostly integer multiples of the speed-related frequency (f_{Speed}) These relationships suggest that the machine vibration in a normal situation is likely to result primarily from mechanical sources such as unbalanced mass of the rotational parts, shaft misalignments, bearing gaps, etc. Considering that the characteristics of the mechanical vibration are partially reflected in the club head vibration, especially in the middle frequency range, as shown in Figs. 9 and 10, it can be ascertained that the machine vibration plays an important role in determining the club head vibration.

4.2. Vibrations generated in the grinding process

The results shown in Figs. 9 and 10 suggest the vibration from the machine is not the sole source of the club head vibration. Then, the grinding process must generate some vibration. Grinding can be considered a material removal process done by many individual cutters randomly distributed on the grinding belt The randomly engaged cutters must generate some random vibration. Possible slip-stick processes in the friction of the club head over the belt surface may also cause some vibration, which may be enhanced by the vibration from other vibration sources and/or the unavoidable variation of the applied feed force. As shown in Fig. 2, the drive wheel tread is composed of inclined rubber ridges. Although the grinding belt can largely smooth them, there must be some geometric variations on the grinding surface. Furthermore, the contact stiffness on the surface over a ridge may be different from that between two ridges. These irregularities may generate some high frequency vibration, as its basic frequency is equal to the number of rubber treads multiplied by the drive speed.

As shown in Figs. 5 and 10, the low frequency vibration spectra (<6.3 Hz) measured on the club head could be largely different from those measured on the machine. The different trends suggest that the low frequency vibration of the workpiece does not have much association with the machine vibration but it is mostly generated during the grinding process. This study found that the low frequency vibration components were related to the working habits described in Section 2.1, as these spectrum components measured with the workers performing stable grinding were much less than those measured with the other workers making a lot of quick, swinging motions during the grinding. As these vibration components are not of concern for hand-transmitted vibration exposure (ISO 5349–1, 2001), it is not necessary to change the workers' practice and to reduce these low frequency components if they do not cause any other adverse effects or safety concerns.

4.3. Vibration transmissions and system responses in the grinding process

As shown in Fig. 9, the grinding vibration has negligible influence on the large-wheeled machine vibration. This is because the grinder drive wheel mass (11 kg) and the machine mass (350 kg) are much larger than the mass of each club head (<0.3 kg); as a result, the possible grinding force may be too small to cause any significant change in the machine vibration. Some significant influences of the grinding on the small-wheeled machine vibration are observed at more than 63 Hz. This may be because the small wheel has less mass than the large wheel and more vibration was generated on the small-wheeled machine, as presented in Tables 2 and 3. The frequency range influenced suggests that the grinding itself mostly generates the vibration at frequencies above 63 Hz. The increased differences between the machine vibration and club head vibration in the high frequency range shown in Figs. 9 and 10 also suggest that the grinding process may generate many high frequency components.

Increasing the push force on the club head increases the coupling between the club head and the machine. The increase coupling can usually increase the vibration transmission from the machine to the club head. It can also increase the grinding engagement and results in higher vibration. For these two reasons, it is reasonable to hypothesize that the push force applied on the club head is correlated with the club head vibration. However, the finger coupling force measured in this study was not well correlated with the club head vibration. This is likely to be because the finger coupling force is not equal to the push force in general. The finger coupling force measured with the adapter used in this study generally includes both grip and push forces applied on the club head in a single direction. The coupling force can be used approximately to represent the push force only when the measurement direction is largely aligned with the direction normal to the grinding surface. Furthermore, it is unknown how much the force measured with the fingers-held adapter actually reflects the true coupling force. Further study is required to develop or identify a reliable method for measuring the push and grip forces separately to determine the exact relationship between the club head vibration and the push force.

The grinding efficiency and quality of the golf club head are affected by both the machine vibration and the dynamic response of the workpiece. The vibration can influence the grinding engagement, similar to the push or feed force effect. If the transmitted vibration and/or grinding vibration includes the resonant frequencies of the club head and/or the coupled wheel-belt-head-hand-arm system, the resonances are excited. The excited resonances may further enhance the grinding vibration (Ganeshraja and Dheenathayalan, 2014). Each club head tested in this study is a light-weight stiff shell structure with little damping. It should exhibit high-frequency resonances with magnitudes much larger than the machine vibration. These features match with the high vibration peaks shown in Figs. 5, 9 and 10. This suggests that some of these peaks are likely to be associated with the resonances of the club heads. These resonant peak frequencies may not match with those of the machine vibration, as shown in Figs. 9 and 10.

Theoretically, the response of the club head to its excitations is affected by its constraints. This was unintentionally proven in the experiment on the simulated test station. Because the club head was tightly held by a fastener fixed on a large mass, as shown in Fig. 4, the club head vibration values measured on the test station listed in Table 4 are much less than those listed in Tables 2 and 3 measured on the club head held by the fingers or hands in the real grinding process. Although the data from the simulated test may not have much value for risk assessment, it demonstrates that the club head vibration can be reduced by adding mass and damping. This concept is similar to that used for reducing the handheld bucking bar vibration in a riveting process (McDowell et al., 2015).

4.4. Contradictory phenomena and limitations of the study

Theoretically, the vibration force resulting from the unbalanced mass is proportional to the square of the mass rotation speed. This explains why the first vibration peak of the machine vibration in the middle frequency range substantially increased with the increase in the speed, as shown in Fig. 7. The increased machine vibration can be passed to the club head, as the first peak vibration of the club head is highly correlated with that of the machine, as shown in Figs. 9 and 10. This means that increasing the machine speed may increase the first major peak magnitude of the club head acceleration. However, this does not mean that the weighted acceleration is also increased. Instead, increasing the machine speed generally reduced the weighted acceleration of the club head, as indicated in Table 3. This is partially because increasing the speed moves the first major peak vibration to a higher frequency that corresponds to a lower weighting (ISO 5349–1, 2001). This is also because increasing the machine speed increases the grinding efficiency so that less grinding time and coupling force are required to remove the same amount of materials from the club head surface; as a result, the averaged acceleration may not be increased. This is not the case in the laboratory test. On the simulated test station, the club head was kept in contact with the grinding belt by a constant push force (20 N) and was continuously ground without any break time during the entire test period. The increased machine speed must also increase the amount of the material removed from the club head and more vibration energy must be involved in such a process. As a result, the club head vibration is likely to increase with the increase in machine speed. This explains the results shown in Table 4.

The unbalanced mass of a worn wheel could be larger than that of a normal wheel, as the wheel may wear unevenly. Theoretically, this should result in a larger vibration peak at the frequency corresponding to the machine speed. This, however, was not obvious, as shown in Fig. 8(b). This suggests that the vibration increase due to the use of worn wheel indicated in Table 4 was not likely to primarily result from the increased unbalanced mass of the worn wheel. The increase may be associated with the increased geometric unevenness of the worn wheel tread.

The replacement of the original plastic foot pad of the machine with the new rubber foot pad basically reduces the suspension stiffness of the machine on the floor. This can reduce the fundamental resonant frequency of the machine body so that the vibration transmitted to the floor or from the floor to the machine can be reduced. This is also useful to reduce the vibration interactions among the grinding machines installed on the same floor. Theoretically, however, the reduced suspension stiffness may or may not reduce the vibration of each machine, depending the excitation frequency. As shown in Fig. 8(a), the new foot pad increased the middle-frequency (20–250 Hz) vibration but it reduced some high-frequency components. Because the frequency-weighted acceleration depends primarily on the components in the middle frequency range, as shown in Fig. 6, the use of the new pad is likely to increase the weighted value. This contradicts the laboratory test results presented in Table 4. Further studies are required to confirm and understand the contradiction. This also suggests that the simulated test station and experimental method should be further examined and improved.

As above-discussed, many factors may affect the club head vibration. It is beyond the scope of this study to fully investigate all these factors and their interactions. The number of subjects, club head models, and machines used in the experiments may not be sufficient to provide a representative sample of the vibration exposure among the grinding workers at the workplace. Therefore, the results presented in Tables 1–3 should be used with caution for any risk assessment using the standard method defined in ISO 5349–1 (2001). However, these limitations should not affect the major vibration sources and the basic vibration characteristics of the club heads identified in this study.

4.5. Potential methods for controlling the vibration exposure of the grinding workers

The sanding/grinding/polishing processes of handheld workpieces expose the workers to not only vibration but also other hazards such as noise, dust, heavy metal particles, and potential hand injuries. According to the general guidance proposed by the UK Health and Safety Executive (HSE, 2005), the first strategy for controlling the vibration exposure is to minimize the vibration at the design stages of a product and in its manufacturing methods and procedures. For large-scale production, some advanced automation technologies such as robot grinding arms may be considered to reduce the labor-intensive sanding/grinding tasks (Liu, 2016). The labor-intensive tasks involved in the vibration exposure may only be used when it is too expensive and technically difficult to use other methods and technologies. In such cases, some administrative and engineering approaches should be considered to minimize the exposure of the workers performing the tasks.

4.5.1. Administrative controls—The potential administrative controls may include the following aspects:

- **Inform workers of the potential health effects of prolonged and intensive exposure to hand-transmitted vibration.**
- **Provide workers, especially new workers, with technical and ergonomic training.** Some workers may grip and push too hard on a workpiece to attempt to achieve high productivity. This may increase grip force and vibration transmission without increasing working efficiency. The training should be designed to help workers to apply appropriate hand forces, postures, grinding and inspection procedures to keep the productivity without increasing the vibration exposure.
- **Avoid prolonged vibration exposure by revising the pay system.** The current piecewise pay system encourages excessive vibration exposure. This pay system should be revised to discourage the excessive exposure. For example, the exposure time or the number of workpieces on each working day can be controlled based on the required or desired daily vibration exposure limit using the formula [<mi>] defined in ISO 5349–1 (2001). If the daily exposure dose, A(8), is to be kept below the Action Value of 2.5 m/s^2 as presented in EU Directive (2002) or ANSI S2.70 (2006), the actual vibration exposure time (T) for the vibration magnitudes listed in Table 2 should be controlled within 1.16 h and 1.41 h, respectively for the workers using the small-wheeled machine and those using the largewheeled machine. The exposure time may be increased if the vibration magnitude is reduced.
- **Spread out the vibration exposure over the whole working day and require each worker to take regular breaks.**
- **Take advantages of job rotation.** If possible, share the grinding tasks among the workers in a manufacturer to minimize the vibration exposure for each worker.
- **Keep workshop temperature in a comfortable range. Avoid blowing cold air from an air conditioner on the hands.**
- **Control noise exposure to as low as possible, at least below an acceptable level (e.g., < 85 dB,** GBZ2.2, 2007).

4.5.2. Engineering controls—Based on the vibration sources and vibration characteristics identified or confirmed from this study and the current knowledge for the vibration control, a set of potential engineering methods for controlling the vibration exposure of the grinding workers are proposed in this study, which are as follows:

1. **Replace machines with low-vibration and low-noise machines.** The machine vibration can be effectively reduced by using high-quality motor, bearings, and well-balanced wheels, and by increasing the alignment of the wheel shaft installation.

2. **Reduce machine vibrations by installing an anti-vibration device on an existing machine.** Some automatic balancing technologies for rotational machines are available (Green et al., 2008). They may also be used for the retrofit of the existing grinding machines.
3. **Regularly monitor machine vibration and maintain grinding machines in good working conditions.**
4. **Optimize the contact irregularities of the drive wheel-grinding belt assembly.** The contact irregularities are likely to be a major contributor to high-frequency grinding vibrations. On the other hand, certain irregularities may be required to achieve the grinding efficiency. Further studies are required to find the balance between the grinding productivity and the vibration exposure.
5. **Increase the effective mass and damping property of the club head.** Many grinding machines are equipped with workpiece seats. Firmly attaching the workpiece to the seat can effectively increase the mass of the workpiece so that the vibration of the workpiece can be reduced. Such a seat should be solidly supported on the floor to avoid any resonance in the grinding process (HSE, 2005). This method may not be applicable for a workpiece that requires frequent adjustments and sweeping movements during the grinding. Alternatively, mass and damping materials can be temporarily attached to the club head during the grinding if this is feasible.
6. **Avoid the resonances of the machine-workpiece-hand-arm system as much as possible.** The natural frequencies of the system should be as far as possible from the major excitation range of 20–40 Hz. The resonant frequencies of the drive wheel related to the connection stiffness of the bearings, the club head resonant frequencies related to the grinding contact stiffness and the hand constraint stiffness, and the resonant frequencies of the workpiece support structure should also be identified and avoided.
7. **Use an appropriate motor speed.** Increasing machine operation speed can increase productivity but it may also sensitively increase the machine vibration, as shown in Fig. 7. The results listed in Table 3 suggest that there may be an optimized operation speed to minimize the club head vibration, which requires further study to identify the optimized speed for the workers.
8. **Isolate the vibration transmission by developing workpiece holders/ accessories.** Workpiece holders can be designed to avoid directly holding the workpiece by the fingers or hands. The holders should also effectively isolate the vibration transmitted to the fingers and hands. The holder can also make the grinding operation safer. This, however, may also reduce the productivity. It may not be applicable for fine grinding that requires frequent adjustments to the grinding area and location. It may be applicable for some grinding tasks requiring removal of large amounts of materials in a given area.
9. **Isolate the club head vibrations from effective transmission to the lingers or hands using vibration-reducing gloves.** Wearing full-finger gloves can reduce

the finger contact stiffness (Dong et al., 2009). This may not reduce the vibration components in the middle frequency range transmitted to the fingers or the frequency-weighted acceleration (Hewitt et al., 2015) but the gloves can reduce very high-frequency components (Welcome et al., 2014). The current frequency weighting may largely underestimate the high frequency health effects (Tominaga, 2005; Nilsson et al., 1989; Barregard et al., 2003; Starck et al., 1990; Dandanell and Engstrom, 1986; Dong et al., 2012). The gloves may actually offer more protection against hand-transmitted vibration exposure than what is judged based on the frequency-weighted acceleration, which may partially explain why the gloves may not reduce the weighted acceleration but they may reduce some symptoms of VWF **(**Jetzer et al., 2003). The coupling force values presented in Table 2 suggest that the applied finger force is unlikely to be very large. This may make the gloves effective for reducing high-frequency vibration transmitted to the fingers in the grinding process. The selected gloves do not have to be anti-vibration gloves certified according to ISO 10819 (2013), as the standardized test can only assure the effective attenuation of the vibration at the palm of the hand along the forearm direction. However, careful consideration must be taken to select gloves which can assure reduction in the high frequency range. Furthermore, the gloves should be chosen so as to not reduce finger dexterity and/or substantially increase the hand grip effort. While the double-glove method that has been used at some workplaces may provide some protection for the workers, further studies are required to evaluate their effectiveness and to optimize the designs or selections of vibration-reducing gloves.

It is emphasized that not every method is applicable to each specific workplace or grinding task. It may also be difficult to use a single method to control the vibration exposure to an acceptable level. A combination of suitable methods may be the best strategy for the vibration control, which can be selected based on their feasibility for implementation, their cost-effectiveness, and their impacts on productivity and workplace safety. The specific technologies required for implementing these methods require further studies.

5. Conclusions

This study confirms that golf club head vibration during the grinding process resulted from the belt grinding machine vibration and the grinding process itself. The major vibration peaks of each machine in the critical middle frequency range (20–250 Hz) are largely associated with the operation speed of the machine, which suggests that the machine vibration of major concern results primarily from mechanical sources such as unbalanced mass of the rotating parts, misalignments of shafts and bearings, tolerances in the bearings, etc. The grinding vibration may result from the geometric irregularities of the grinding interface and the mechanical property irregularities of the grinding system. The dynamic responses of the club head and hand-arm system and the applied hand feed force may also influence the club head vibration. These vibration sources and the mechanism of the system dynamic response suggest that many factors can affect the club head vibration. The significant influencing factors identified in this study include testing subject, grinding machine, machine operation speed, drive wheel condition, club head model, mechanical constraints imposed on the club head during the grinding, and machine foot pad.

These findings suggest that the vibration exposure of the fingers or hands during the grinding process can be controlled by reducing the grinding machine vibration, changing the dynamic properties of the workpiece, and mitigating the vibration transmission in its pathway. Many potential specific methods for vibration exposure control are proposed and discussed. Further studies are required to further examine these methods and to develop economically viable and practically feasible technologies to implement them at workplaces.

Acknowledgments

Disclaimer

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety & Health. The mention of trade names, commercial products, or organizations does not imply endorsement by the U.S. Government.

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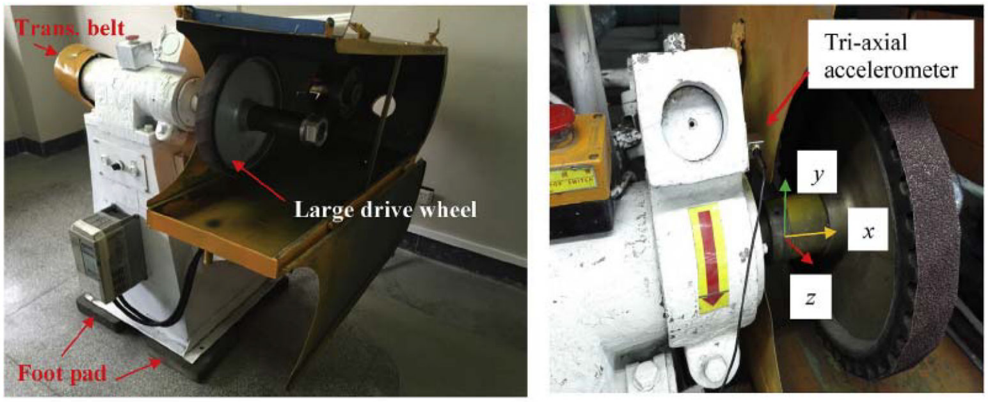
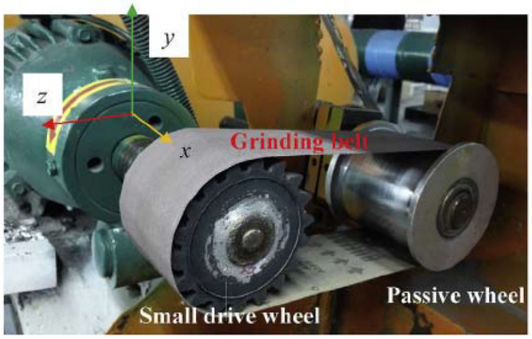
Fig. 1.

A worker is grinding a golf club head at a typical workstation with a belt grinding machine (with a large drive wheel) in a sport equipment manufacturer.



(a) A belt grinding machine with a large drive wheel

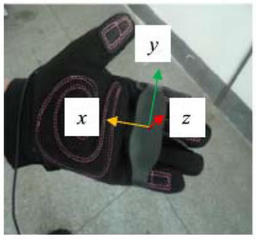


(b) A belt grinding machine with a small drive wheel

Fig. 2.

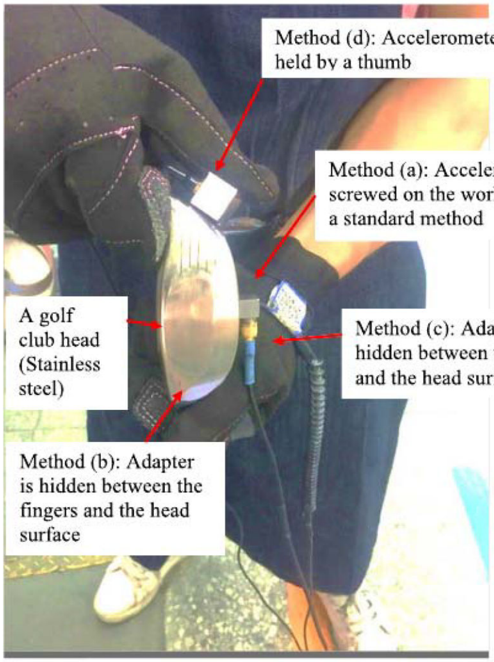
The belt grinding machines used in this study, the location of a tri-axial accelerometer installed on each machine for its vibration measurement, and the measurement coordinate system (*x* along the shaft axial direction; *y* vertical direction; *z* horizontal direction).

(a) Accelerometer screwed on a club head (reference method)



(b) Adaptor held at the fingers

(c) Adaptor held at the palm



(d) The measurement of the vibration on a club head simultaneously using the four methods

Fig. 3.

Four methods for accelerometer installations examined in Experiment I.

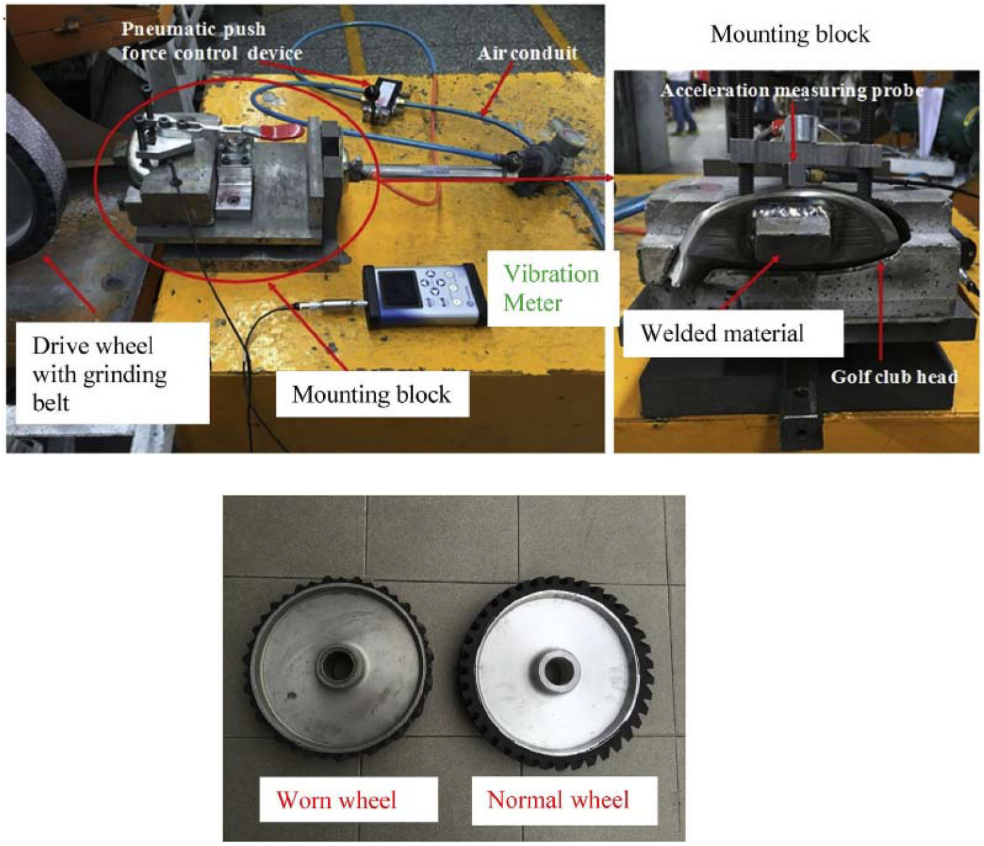
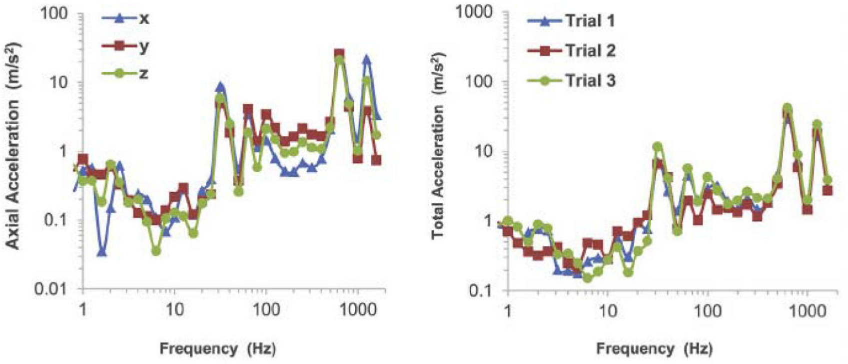
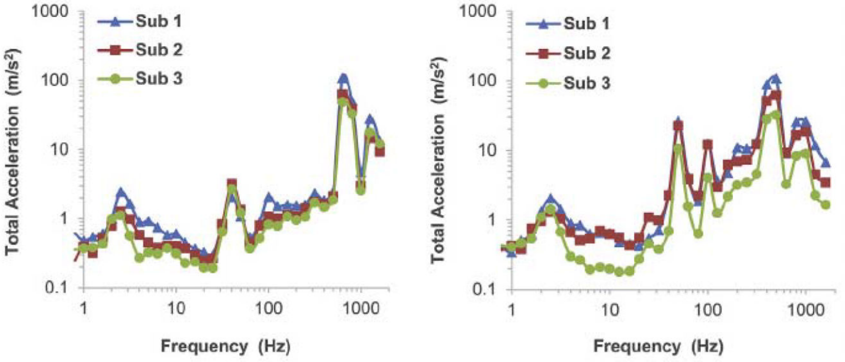


Fig. 4.
A simulated workstation used in Experiment IV for investigating the vibration of a golf club head during its grinding process.



(a) Vibration spectra in three orthogonal directions (larger wheel machine, 1,800 RPM, stainless-steel club head)

(b) Effect of trials on total vibration (1,800 RPM, large wheel machine, stainless-steel club head)



(c) Effect of subjects on total vibration (large wheel machine, 2,400 RPM, titanium club head)

(d) Effect of subjects on total vibrations (small wheel machine, 2,800 RPM, titanium club head)

Fig. 5.

Examples of typical unweighted axial vibration spectra and total unweighted vibration spectra (the vector sum of the accelerations at each frequency in three axes) of a titanium golf club head during its grinding process, which were measured in Experiment III.

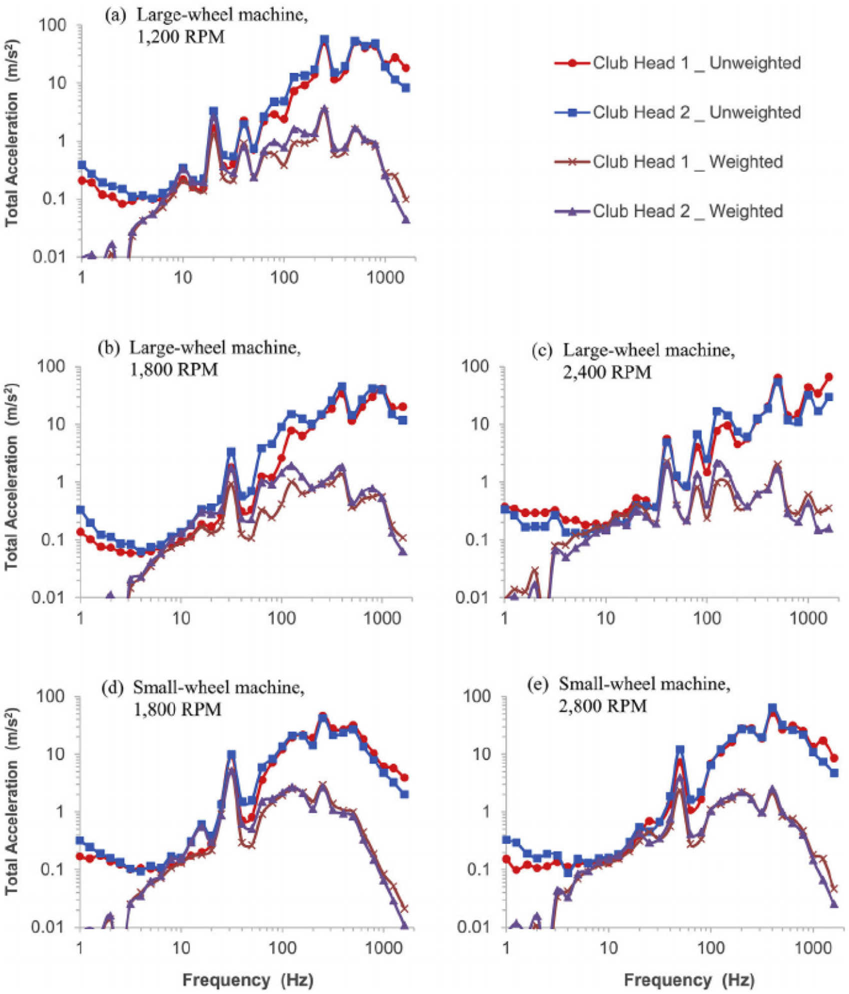


Fig. 6.

Weighted and unweighted vibration spectra of the two models of club heads (Head 1 - Titanium alloy; Head 2 Stainless steel) measured in Experiment III under different operation speeds (1,200, 1,800, 2400 or 2800 RPM) on two different types of grinding machines (Machine with a large drive wheel and Machine with a small drive wheel).

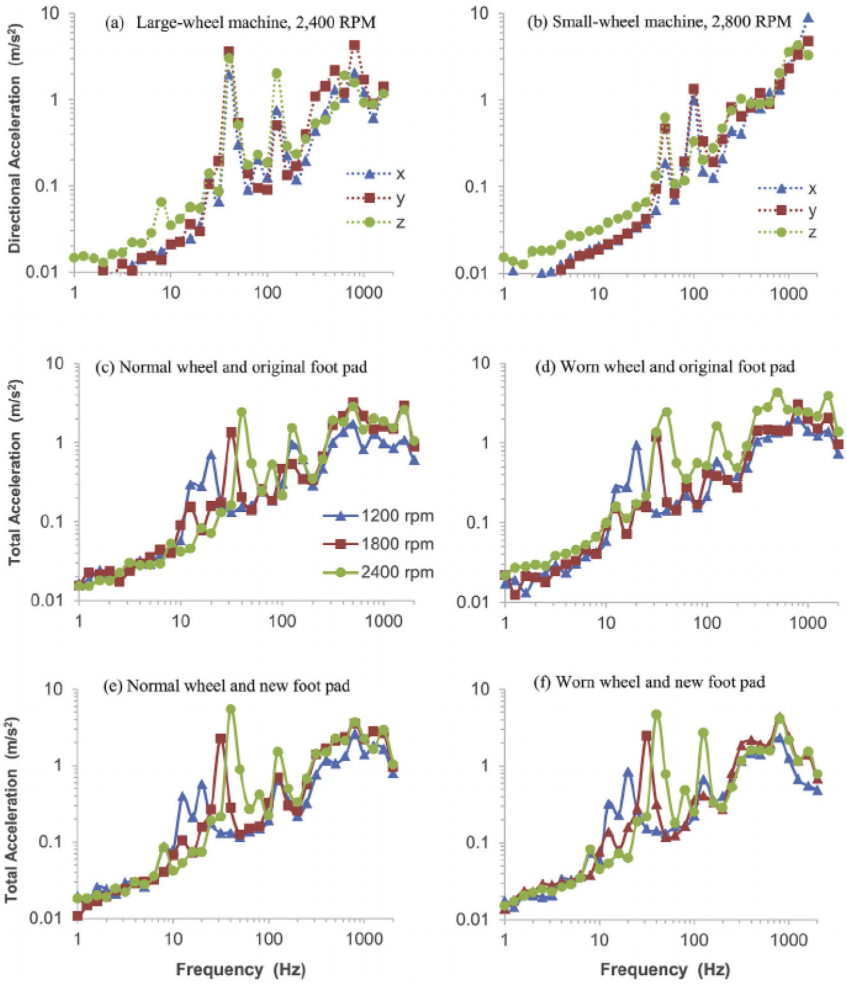
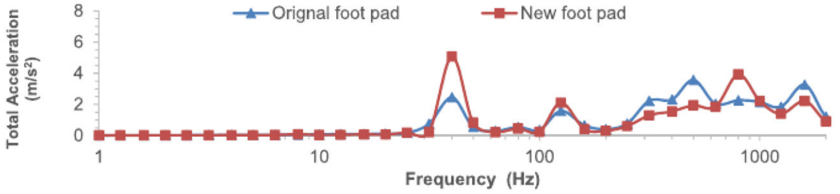
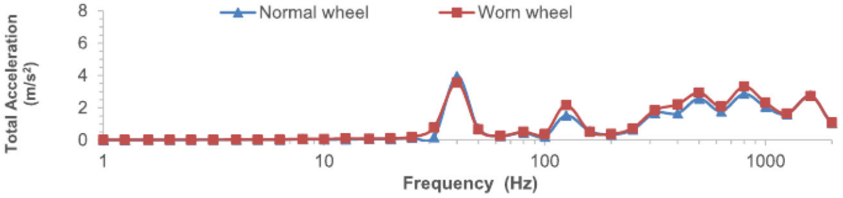


Fig. 7.

The vibration spectra measured in Experiment III on the machines in free-run tests (without performing any grinding task).



(a) Effect of foot pad on machine vibration in free-run test



(b) Effect of the wheel condition on machine vibration in free-run test

Fig. 8.

Effects of foot pad and wheel condition on the machine vibration at 2400 RPM.

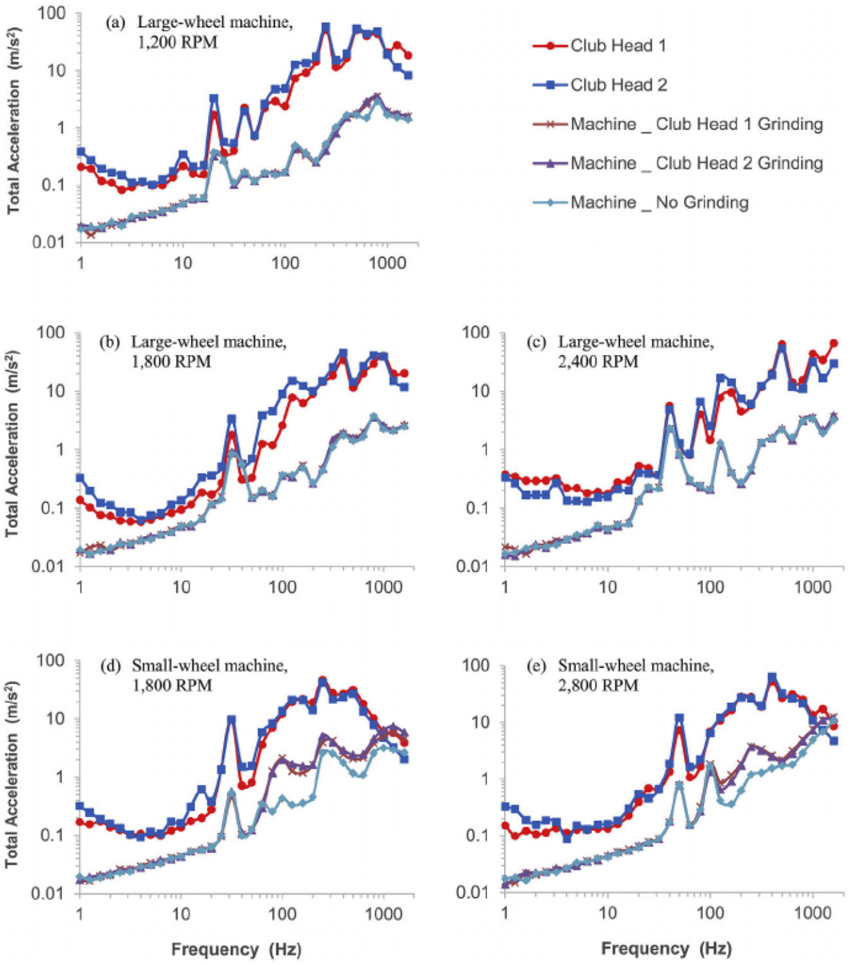
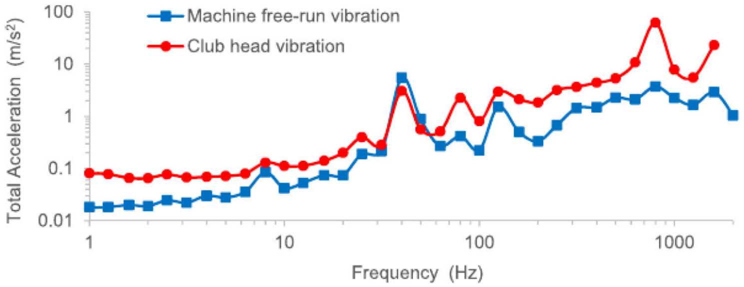
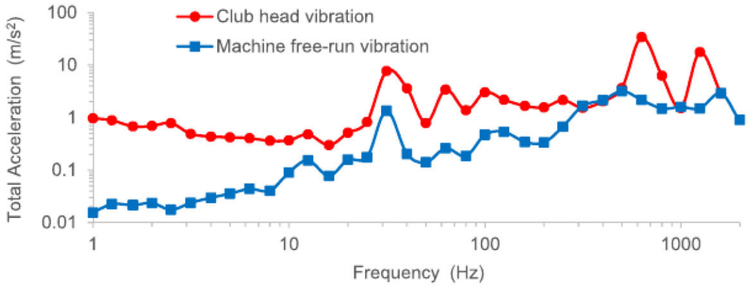


Fig. 9.

The relationships among vibration spectra measured in Experiment III with two models of club heads (Head 1 - Titanium alloy; Head 2 Stainless steel) under different operation speeds (1,200, 1,800, 2400 or 2800 RPM) on two different types of grinding machines (Machine with a large drive wheel and Machine with a small drive wheel).



(a) Titanium club head on normal large-wheel machine with new foot pad at 2,400 RPM



(b) Titanium club head on large-wheel machine with original foot pad at 1,800 RPM

Fig.10.

Examples of the high correlations between the club head and machine vibrations measured in some of the tests in Experiment III.

Table 1

The comparisons of the results measured in Experiment I with the four methods for mounting an accelerometer (one subject but 20 trials were performed for each test treatment).

Method (refers to Fig. 3)	Mean a_{hv}(m/s^2)	STD (m/s^2)	Error to reference	95% Range (m/s^2)	
				Low	High
(a) Reference method	2.42	0.39	Reference	2.24	2.60
(b) Fingers-held adapter	2.34	0.18	3.31%	2.26	2.42
(c) Palm-held adapter	1.57	0.18	35.12%	1.48	1.66
(d) Thumb-held accelerometer	1.83	0.20	24.38%	1.71	1.97

Table 2

Results of the frequency-weighted accelerations and average coupling force measured in Experiment II at a workplace during the grinding of the Titanium alloy club heads under (a) Test Condition I, and (b) Test Condition II. (The bold numbers are the overall mean values and statistics)

Subject	**Trial 1**		**Trial 2**		**Trial 3**		**Mean**		**STD/CV**	
	a_{hv} (m/s^2)	**Force (N)**	**a_{hv} (m/s^2)**	**Force (N)**	**a_{hv} (m/s^2)**	**Force (N)**	**a_{hv} (m/s^2)**	**Force (N)**	**a_{hv} (m/s^2)**	**Force (N)**
(a) Test condition I: Belt grinding machine with a small drive wheel, rotation speed of 2800 RMP, grinding the front surface of a stainless steel club head with a fine grinding belt, the machine is on rubber pad										
1	10.29	10.22	11.17	14.14	10.30	12.03	10.59	12.13	0.50/0.05	1.96/0.16
2	3.66	4.33	4.11	8.24	3.89	11.18	3.89	7.92	0.22/0.06	3.44/0.43
3	4.43	1.85	5.90	9.07	5.30	4.48	5.21	5.13	0.74/0.14	3.65/0.71
Mean	6.13	5.47	7.06	10.48	6.50	9.23	**6.56**	**8.39**		
STD	3.63	4.30	3.67	3.19	3.37	4.14	**3.55**	**3.52**		
CV	0.59	0.79	0.52	0.30	0.52	0.45	**0.54**	**0.42**		
(b) Test Condition II: Belt grinding machine with a large drive wheel, rotation speed of 2400 RPM, grinding the front surface of a stainless steel club head with a fine grinding belt, the machine is on rubber pad										
1	7.55	3.98	7.41	5.36	8.72	6.40	7.89	5.25	0.72/0.09	1.21/0.23
2	5.85	3.13	5.23	2.07	3.83	0.73	4.97	1.98	1.04/0.21	1.20/0.61
3	5.06	9.74	4.57	6.00	5.30	7.13	4.98	7.62	0.37/0.07	1.92/0.25
Mean	6.15	5.62	5.74	4.48	5.95	4.75	**5.95**	**4.95**		
STD	1.27	3.60	1.49	2.11	2.51	3.50	**1.69**	**2.84**		
CV	0.21	0.64	0.26	0.47	0.42	0.74	**0.28**	**0.57**		

Table 3

Comparisons of frequency-weighted acceleration values of two club heads calculated from the vibration spectra measured in Experiment III under three speeds on the two machines.

Machine	**Speed (RPM)**	**Weighted vibration, ah_v Mean ± STD (m/s^2)**	
		Titanium alloy	**Stainless steel**
Large drive wheel, new rubber foot pad	1200	4.88 ± 1.14	6.06 ± 1.49
	1800	2.87 ± 0.56	4.75 ± 1.14
	2400	3.93 ± 0.98	4.41 ± 0.73
Small drive wheel, new rubber foot pad	1800	7.95 ± 2.73	8.33 ± 0.65
	2800	5.58 ± 2.73	6.78 ± 1.07

Table 4

Results obtained from Experiment IV on the simulated test station with a section of stainless-steel welded on a stainless-steel club head.

Treatment no.	**Wheel speed (RPM)**	**Pad at the machine base/feet**	**Drive wheel**	**a_{hv}, mean ± STD (m/s^2)**
1	1200	Ordinary plastic pad	Ordinary	0.86 ± 0.04
2	1800	Ordinary plastic pad	Ordinary	1.12 ± 0.04
3	2400	Ordinary plastic pad	Ordinary	1.84 ± 0.05
4	2400	New rubber pad	Ordinary	1.35 ± 0.05
5	2400	Ordinary plastic pad	Worn	2.37 ± 0.07