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Research Article

An Experimental Study of the Influence of Hand-Arm Posture and Grip Force on the Mechanical Impedance of Hand-Arm System

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In order to investigate the effects of hand-arm posture, grip force, push force, and vibration excitation intensity on the mechanical impedance of human hand-arm system, a test system with a self-developed vibration handle has been prepared. Based on the testing system, the mechanical impedance of the hand-arm system of seven Chinese adult males were tested and calculated under the random vibration excitation with the frequency of 10–1000 Hz. The results reveal that when the frequency is lower (<40 Hz), the hand-arm system with an elbow angle of 180° produces a higher mechanical impedance; when the frequency ranges from 40 Hz to 100 Hz, the hand-arm system with an elbow angle of 90° generates a higher mechanical impedance; while when the frequency is higher (>100 Hz), the hand-arm posture seems to have no obvious effect on the mechanical impedance. Higher grip or push force would increase the frequency corresponding to the peak value of the mechanical impedance and often correspond to a higher mechanical impedance in a specific frequency range (30–200 Hz). When the frequency is lower (<140 Hz), vibration intensity has certain effects on the mechanical impedance of the hand-arm system. In conclusion, vibration intensity does not directly affect the mechanical impedance, but an increase in grip or push force often causes an increase in mechanical impedance and a higher frequency that corresponds to the peak of mechanical impedance.

1. Introduction

When the agricultural machinery and equipment are working in the field, strong vibrations are inevitably produced due to the low levelness of the farmland, large motion range of the working device, high running speed of the transmission system and its own structural characteristics, and the vibrations will be passed to the body of the operator through the seat, steering wheel, handrails, and pedals. According to different body parts that are influenced by the transmitted vibrations, the vibrations can be divided into whole body vibration and local vibration. Whole body vibration mainly refers to the vibration transmitted to the body through the supporting surface, such as the seat. Local vibration, also known as hand-transmitted vibration, is the mechanical vibration or shock acting on or transmitted to the hand-arm system through the hand or fingers from the steering wheel and operating armrest [1, 2]. Some vibrating tools and machines, such as crushers, rock drills, and grinders, are widely used in many industrial occasions. The workers who manipulate this kind of tools or machines for a long time may feel tingling and numbness in their hands, the severity of which usually increases with stronger vibration intensity of the tool. In severe cases, it may cause physical discomfort and loss of control of the tool [3]. These acute effects usually disappear shortly after stopping the use of the tool. However, prolonged exposure to such high-intensity hand-transmitted vibrations can cause a series of diseases in the blood vessels, sensory nerves, and musculoskeletal parts of the human hand-arm system. These diseases are collectively referred to as "arm vibration syndrome," also known as Raynaud's disease. For legal occupational diseases, the main symptoms are vibration white fingers [4, 5]. Figure 1 shows the symptoms and signs of vibration white fingers. According to previous reports, vibration white fingers are difficult to treat and require a long recovery period. The symptoms of some patients continue to deteriorate even after the vibration operation is stopped. For example, a study revealed that some patients with Raynaud's disease could not recover from vibration exposure even after more than 20 years [6].

Hand-transmitted vibration will cause some damage to the health of the operators of vibrating machinery, especially under high vibration intensity and long exposure to vibration. Hence, the harm caused by hand-transmitted vibration is a particularly prominent problem. At present, there is an increasing demand for the protection of the health of vibration tool operators. Therefore, it is critical to effectively control the hand-transmitted vibration to minimize the harm to the human hand-arm system.

So far, relevant research has been mainly focused on the vibration source of the tool itself, aiming to optimize the structure of the tool, reduce the strength of hand-transmitted vibration, and alleviate the adverse effects of vibration on the human hand-arm system. However, there has been little research on the human hand-arm system under hand-transmitted vibrations, such as the absorption and transmission characteristics of vibration energy in the hand-arm system, the response of the system to hand-transmitted vibration, and its relationship with vibration excitation. To minimize the impact of hand-transmitted vibration on human health, it is also highly necessary to study the characteristics of vibration transmission in the human hand-arm system, as well as some physical factors of vibration such as hand-arm posture, vibration frequency and amplitude, and gripping force. Exploration of the transfer law of vibration energy in the hand-arm system can not only help to improve and optimize the structure of the vibration machinery but also provide important reference for monitoring the occupational health of workers and the early diagnosis and prevention of arm vibration disease.

Investigation of the biodynamic response of the human hand-arm system can facilitate a better understanding of the mechanism underlying the damage caused by vibration, as well as help to formulate frequency weighting factors for the evaluation of the risk caused by vibration exposure. Besides, it may also facilitate the development of methods or devices for the isolation of the hand-arm system from vibration. Some studies have been carried out on the biodynamic responses of the hand-arm system, including apparent mass, apparent stiffness, and mechanical impedance, and most studies are focused on mechanical impedance. The main research findings are as follows. Lundström et al. measured the mechanical impedance of the hand-arm system in the frequency range of 20–1500 Hz and found that the mechanical impedance is strongly dependent on the frequency of vibration [7]. Burström studied the mechanical impedance of the human hand-arm system with random vibration under different experimental conditions and statistically analyzed whether the conditions have an effect on the amplitude and phase of the mechanical impedance. The results were further compared with those from other studies using the sinusoidal excitation. The results showed that the vibration level and vibration stimulation frequency have a very significant effect on the mechanical impedance of the hand-arm system. The increase in grip or push force will cause the increases of impedance [8]. Hempstock and O'Connor evaluated the measurement accuracy of the mechanical impedance of the human hand-arm system and found that when the frequency is lower than 25 Hz, there were certain differences between the measured impedance values [9]. Gurram et al. employed the impedance testing technique of the driving point to study the biodynamic response of the human hand-arm system under sinusoidal and random excitation and found that, within a certain frequency range, the response characteristics of the hand-arm system caused by sinusoidal excitation and random excitation are significantly different, indicating the nonlinear characteristics of the hand-arm system [10]. Dong et al. proposed a method to measure the mechanical impedance of the finger and the palm and studied the distribution characteristics of mechanical impedance. The results showed that, at lower frequencies (≤40 Hz), the mechanical impedance of the palm was significantly higher than that of the finger; when the frequency was increased to 100 Hz, most of the mechanical impedance was still distributed in the palm; when the frequency was above 160 Hz, the mechanical impedance of the finger was close to or slightly higher than that of the palm. They also discussed the basic distribution characteristics of mechanical impedance in the finger and palm under vibration in three orthogonal directions [11, 12]. Based on a theoretical analysis of the three-degree-of-freedom and four-degree-of-freedom biomechanical models of the human arm, Li studied the effects of vibration frequency, vibration intensity, hand-arm posture, and gripping force level on the mechanical impedance of the hand-arm system and found very significant relationships among these factors [13]. Dai et al. described mechanical impedance from the

Figure 1: Symptoms and signs of vibrating white fingers.

perspective of vibration mechanics and biomechanics and designed a quantitative detection system for the muscle rigidity symptoms of Parkinson's disease [14].

From the above literature, it can be seen that, in recent years, great progress has been made in research on the vibration transmission of the hand-arm system. However, in many studies, adult males in Europe and the United States were taken as the subjects, whose physical characteristics are very different from those of Chinese adult men. Hence, it remains unclear whether the previously reported biodynamic characteristics and vibration transmission characteristics of the hand-arm system can also be applied to Chinese adult males, and little is known about whether the relevant results and conclusions can be directly used to guide the optimization design for vibration reduction of machines in China.

The mechanical impedance of the human hand-arm system is closely related to the tension of soft tissues such as arm muscles. In the process of operating the machine and tools, hand-arm posture and hand force are the main factors that affect the muscle tension and should be two key factors in testing the mechanical impedance of the hand-arm system. Therefore, this study intends to test the effects of hand-arm posture and hand force on the mechanical impedance of the hand-arm system under different vibration intensities.

2. Materials and Methods

2.1. Research Subjects. The subjects of this experiment were the right arms of seven healthy right-handed adult males with no history of vibration exposure. The anthropometric parameters measured according to GB/T 5703-2010 [15] are shown in Table 1.

The volume of the hand was measured by the Archimedes drainage method, with the wrist just being immersed in water. The maximum grip diameter refers to the linear distance between the middle finger point (ph III) and the most protruding part of the thumb knuckle when the fingertip of the thumb touches the middle fingertip. The test results of anthropometric parameters in Table 1 show that the hand-related parameter values are significantly lower than those of western subjects in hand-transmitted vibration-related tests. At the same time, in this experiment, there were also some differences in anthropometric parameters among different subjects, which might be utilized to study the influence of hand size on the hand-transmitted vibration later.

2.2. Definition of Mechanical Impedance of the Hand-Arm System. Mechanical impedance refers to the obstruction of the mechanical structure on the vibration transmission and can be obtained by calculating the ratio of the force F acting on the system to the speed V generated due to the force at the action point. The human arm is a musculoskeletal system consisting of muscle and bone parts. The bone has a large inertia, and the muscle has rigidity, viscosity, and inertia. These mechanical characteristics are collectively called arm impedance or arm mechanical impedance [16]. According to the standard GB/T 19740-2005 [17], the free mechanical impedance $Z(\omega)$ of the driving point of the hand-arm system is defined as the complex ratio of the excitation force $F(\omega)$ applied at the frequency and the vibration velocity $V(\omega)$ caused at the same frequency, and ω is the vibration angular frequency. For all other connection points, the system is free, which means that the applied external force is zero, namely,

$$Z(\omega) = \frac{F(\omega)}{V(\omega)}. \tag{1}$$

It should be noted that the mechanical impedance value of a hand-arm system is generally a complex number, that is, it has a real part and an imaginary part. Hence, it can also be expressed by mode and phase, and the real part is the mechanical resistance that reflects the absorption and dissipation of vibration energy. In this study, the hand and arm are regarded as a system whose vibrations in the three axes are independent under the biodynamic coordinate system (see Figure 2), as specified in ISO 5349-1-2001 [18]. In this test, the mechanical impedance was measured along the Z_h direction (along the forearm) specified in the human biodynamic coordinate system, which is the main vibration exposure direction of many hand-held power tools during operation. Besides, in this direction, the mechanical impedance value of the entire arm is also the highest [11].

2.3. Calculation of the Mechanical Impedance of the Hand-Arm System. In the experiment, the vibration handle was tested first in the contactless state. The sensor signal on the finger side was used to represent the vibration characteristics of the vibration handle. Therefore, the force signal and acceleration signal on the finger side were measured when subjects did not hold the handle. The mechanical impedance of handle (Z_{handle}) was calculated by the integral of acceleration value, Fourier transform of force value and velocity value in time domain and the calculation of equation (1). Similarly, the force signal and acceleration signal on the finger side and the palm were, respectively, measured when the subjects held the handle. The mechanical impedance of the finger (Z_{finger}) and the palm (Z_{palm}) were calculated in the same way as the calculation of Z_{handle}. Finally, the mechanical impedance value of the entire hand-arm system was obtained by subtracting Z_{handle} from Z_{finger} plus Z_{palm}.

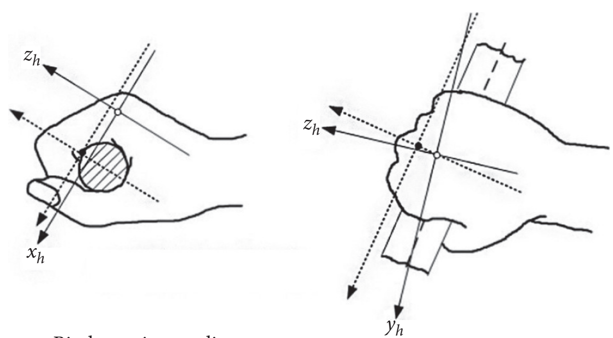
Assuming that the force values measured by the two force sensors on the finger side of the subject are F_1 and F_2 and the force values measured by the two force sensors on the palm side are P_1 and P_2, respectively, the finger force (F_{finger}) and palm force (F_{palm}) can be expressed as follows:

$$\begin{aligned} F_{\text{finger}} &= F_1 + F_2, \\ F_{\text{palm}} &= P_1 + P_2. \end{aligned} \tag{2}$$

The acceleration values measured on the finger side and palm side were integrated once to obtain the velocity value on the finger side (V_{finger}) and palm side (V_{palm}), respectively. Then, the force value $F(t)$ and velocity value $V(t)$ in time domain were converted into force value $F(\omega)$ and velocity value $V(\omega)$ in frequency domain by Fourier

Table 1: Anthropometric measurements of the subjects.

Subject number	Height (cm)	Weight (kg)	Length of the hand (cm)	Width of the hand (mm)	Thickness of the hand (mm)	Volume of the hand (ml)	Maximum grip diameter (mm)	Length of the upper Arm (cm)	Length of the forearm (cm)
1	183.0	100.0	20.1	89.4	39.8	400.0	96.5	37.7	47.1
2	170.0	60.0	20.0	85.5	24.5	350.0	97.2	34.5	45.2
3	171.0	61.0	16.7	80.2	24.7	300.0	85.7	31.7	40.5
4	169.0	58.0	17.4	83.5	29.7	320.0	91.4	32.1	42.2
5	173.0	70.0	17.1	83.3	25.6	310.0	90.7	33.3	43.9
6	176.0	78.0	19.8	88.5	31.7	380.0	97.7	35.4	46.1
7	165.0	62.0	15.2	78.4	23.1	270.0	81.6	30.6	39.6



—— Biodynamic coordinate system

····· Fundamental coordinate system

Figure 2: Hand grip coordinate system.

transform. In equations (3) and (4), the mechanical impedance value on the finger side (Z_{finger}) and the palm side (Z_{palm}) can be obtained as follows:

$$Z_{\text{finger}}(\omega) = \frac{F_{\text{finger}}(\omega)}{V_{\text{finger}}(\omega)}, \tag{3}$$

$$Z_{\text{palm}}(\omega) = \frac{F_{\text{palm}}(\omega)}{V_{\text{palm}}(\omega)}. \tag{4}$$

Finally, the mechanical impedance (Z) of the hand-arm system can be expressed by the following formula:

$$Z = Z_{\text{finger}} + Z_{\text{palm}} - Z_{\text{handle}}. \tag{5}$$

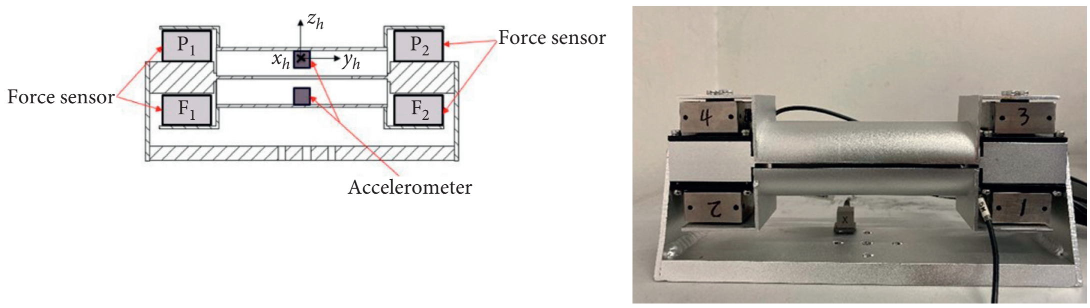
2.4. Mechanical Impedance Test of the Hand-Arm System

2.4.1. Test Equipment. In this study, a self-developed vibrating handle was used. The grip part of the test handle was 40 mm in diameter, 120 mm in length, and 2 mm in thickness. Figure 3 shows the structural schematic and physical diagram of the vibrating handle. In order to ensure its mechanical properties and avoid resonance within the analysis range, the vibrating handle was made of aluminum alloy, which has the characteristics of light weight and high rigidity. The handle was evenly divided into the upper and lower parts at the center line, which were connected by bolts. The middle of each part was equipped with a three-dimensional acceleration sensor, of which the upper half was used to measure the vibration response at the palm and the lower half was used to measure the vibration response at the fingers. Such installation method could provide the reliability of the vibration response test [19]. It is worth noting that the grip part of the vibrating handle was cylindrical and its inside was of a curved surface, which was not conducive to the installation of the acceleration sensor. Therefore, a small rectangle block was welded on the inner surface so that the acceleration sensor could be fixed on the surface of the block. The rectangular block had a flat surface and should be parallel to the middle bracket of the vibrating handle in the welding process and close to the center of the vibrating handle. Both ends of each part were, respectively, fixed with two three-dimensional force sensors on an aluminum alloy strip bracket, wherein the force sensor was fixed by bolts, and the acceleration sensor inside the vibrating handle was fixed with strong glue. All sensors were installed following the instructions. In addition, a clamp was designed to connect the vibrating handle to the vibrating table. The vibrating handle developed in this study can not only measure the vibration response of the finger side and palm side at the same time but also directly measure the grip and push force exerted by the hand-arm system. Therefore, a force plate device for measuring push force was not required.

The three-dimensional force sensor was used to measure the static and dynamic force at the driving points of the palm side and finger side at the same time. Through proper signal processing, the static and dynamic fractions in the force signal measured by each force sensor can be obtained. Figure 4 is a schematic diagram of the contact force, grip force, and push force of the hand, assuming that the static forces measured by the two force sensors on the palm side are P_1 and P_2 and those on the finger side are F_1 and F_2. According to ISO 10819-2013 [20], the static grip force (F_g) and push force (F_p) can be defined as

$$\begin{aligned} F_g &= F_1 + F_2, \\ F_p &= P_1 + P_2 - (F_1 + F_2). \end{aligned} \tag{6}$$

During the test, by rotating the shaker cylinder by 90°, the shaking table could be perpendicular to the horizontal plane so that the direction of the vibration excitation generated by the shaker could meet the Z_h direction of the test



(a) (b)

Figure 3: Vibration handle. (a) Structural sketch. (b) Physical map.

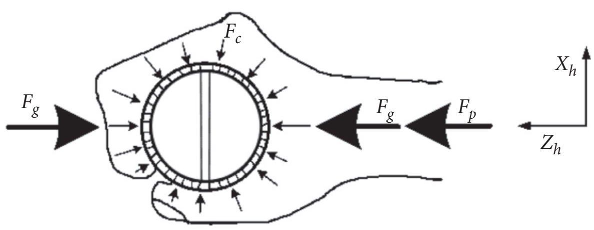


Figure 4: Sketch map of hand contact force (F_c), grip force (F_g), and push force (F_p).

(along the forearm). Figure 5 is the schematic diagram of the mechanical impedance test process (taking the subject's hand-arm posture at 90° as an example).

2.4.2. Test Design. According to the literature, the posture of the hand-arm system, grip force, push force, vibration intensity, and individual differences all have certain effects on the mechanical impedance of the human hand-arm system. Since individual differences are very complex, the research has been mainly focused on the influence of hand-arm posture, grip force, push force, and vibration intensity on the mechanical impedance of the human hand-arm system. In order to investigate the effect of hand-arm posture on the mechanical impedance, we tested and calculated the mechanical impedance of the subjects when the elbow angle of the hand arm was 90° and 180°, respectively. To investigate the effect of grip force on the mechanical impedance, we tested and calculated the mechanical impedance of the subjects when the grip force was 10, 30, and 50 N, respectively. Similarly, to assess the effect of push force on the mechanical impedance, we determined and calculated the mechanical impedance of the subjects when the push force was 10 and 30 N, respectively. Finally, because the usual research range of vibration intensity is 3.5–10 m/s^2, we tested and calculated the mechanical impedance of the subjects under the vibration intensity of 5 and 10 m/s^2, respectively. The test design is shown in Table 2.

Figure 6 shows the two hand-arm postures used in the mechanical impedance test of the hand-arm system.

2.4.3. Experimental Procedure. First, the parameters for the vibration table and data acquisition card were set. The excitation mode was set to broadband random vibration of 10–1000 Hz, and the vibration intensity was 5 m/s^2. In order to make the collected signal as close as possible to the real signal in the studied frequency range, the sampling frequency was set as 5000 Hz. After setting of the parameters, the vibrating handle was fixed on the vibrating table. It should be noted that the vibrating handle and the surface of the vibration table cannot be loosened. Then, the vibration characteristics of the empty handle were tested, so as to eliminate the influence of the mechanical impedance of the vibrating handle itself on the test results when calculating the mechanical impedance of the hand-arm system. At the same time, analysis of the vibration characteristics of the handle showed that there was no obvious resonance phenomenon in the handle in the frequency range studied. Therefore, the vibrating handle could meet the test requirements. All subjects were required to dress lightly and not to wear a coat or rings and watches to minimize the influence of clothing on the test results, and the subjects were tested in a random order. Subsequently, the subjects were required to take the postures according to the test requirements and hold the vibrating handle with appropriate force. Vibration exposure started after the correct postures and the required grip and push force were maintained. During the test, the subjects needed to observe the display screen of the force signal to maintain the grip and push force at levels required by the test (fluctuations within 3 N were allowed). If the subject could keep the grip and push force within the range required by the test, the vibration signal frequency of the hand-arm system would not change significantly in 20 s of vibration exposure. Furthermore, at higher hand force levels (grip force 50 N and push force 30 N), it would be difficult for the subjects to maintain hand force at this level for a long period of time. Therefore, the test of each combination of different test factors lasted for approximately 30 s. Each subject performed 12 trials under one vibration intensity. To avoid the possible impact of hand fatigue on the test results, after the end of each test, the subject would be allowed to take a three-minute rest before taking the next test. Then, the vibration

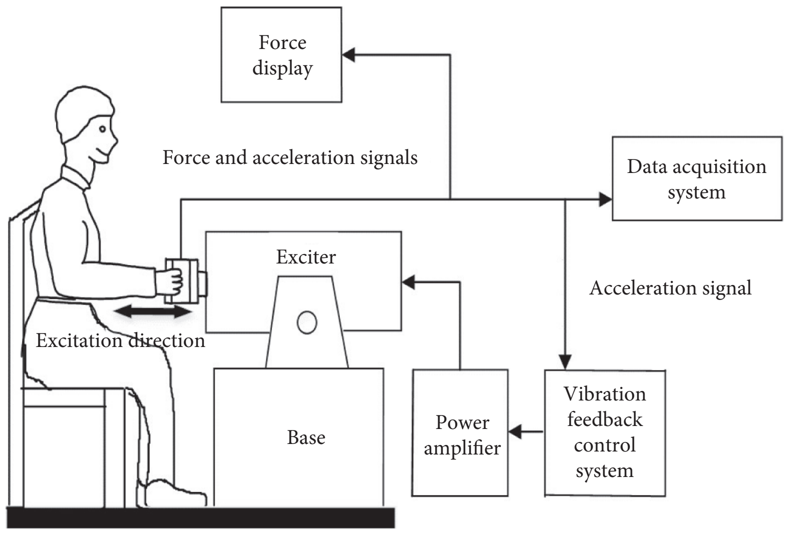
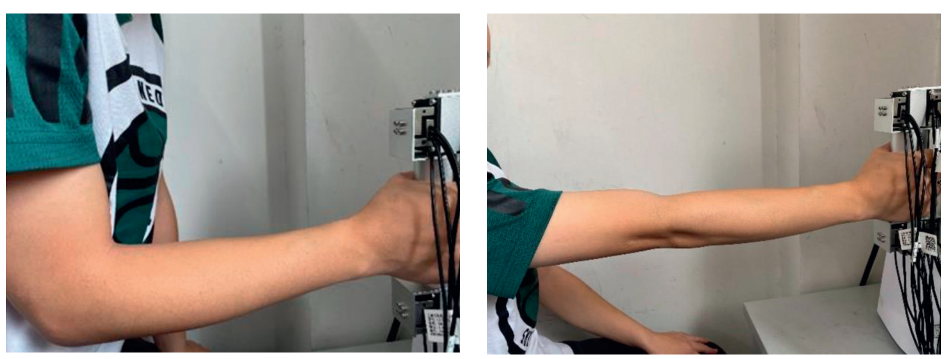


Figure 5: Schematic diagram of the mechanical impedance measurement process of the hand-arm system.

Table 2: Levels of different test factors.

Hand-arm posture	Vibration intensity (m/s^2)	Grip force (N)	Push force (N)
Elbow angle 90°	5	10 30	10
Elbow angle 180°	10	50	30



(a) (b)

Figure 6: Hand-arm posture in the mechanical impedance test. (a) 90° elbow angle. (b) 180° elbow angle.

excitation intensity of the vibration table was adjusted to 10 m/s^2, and other parameter settings were kept unchanged to repeat the above test.

3. Results and Discussion

Matlab software was used to calculate the mechanical impedance amplitude of the human hand-arm system, and the results were expressed at the center frequency point of 1/3 octave in the frequency range of 10–1000 Hz.

3.1. Influence of Individual Differences of Subjects on Mechanical Impedance. The hand-arm posture is the main factor affecting the mechanical impedance [21]. Therefore, we principally discussed the effect of individual differences on mechanical impedance under two different hand-arm postures. Furthermore, we set other test conditions to low strength state (vibration intensity was 5 m/s^2, the push force was 10 N, and the grip force was 30 N) to assure the accuracy of the results. The mechanical impedance amplitudes of seven subjects were calculated by the integral of acceleration value, Fourier transform of force value and velocity value in time domain and the calculation of equation (1). The results are shown in Figure 7.

Observations showed that, under two different hand-arm postures, the amplitude of mechanical impedance of the hand-arm system was only different among individual subjects at low vibration frequencies (<100 Hz), but when the frequency was above 100 Hz, the individual differences

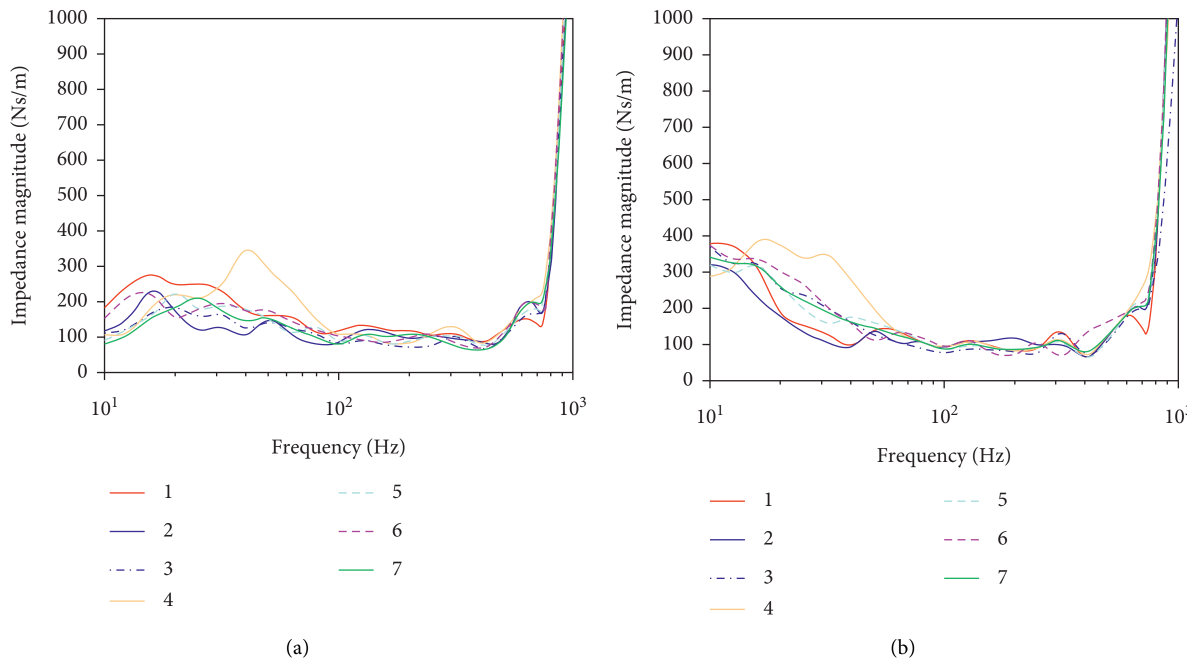


Figure 7: Amplitude of mechanical impedance of the hand-arm system for different subjects ($5\,m/s^2$ vibration magnitude, 30 N grip force, and 10 N push force). (a) 90° elbow angle. (b) 180° elbow angle.

among the subjects showed no obvious effect on the mechanical impedance amplitude. Figure 7(a) shows that when the elbow angle was 90° and the frequency was lower than 14 Hz, the amplitude of mechanical impedance of the hand-arm system increased with increasing hand volume, hand length, hand width, and arm length. The large volume of hand means relatively large apparent mass of the arm system, which would result in a stronger coupling effect with the vibrating handle. In addition, it was observed that, in the frequency range of 30–100 Hz, a smaller hand volume usually corresponded to a higher mechanical impedance amplitude, with a peak value at around 40 Hz, possibly because resonance occurs in the hand-arm system at this frequency. Figure 7(b) shows that when the elbow angle was 180°, the individual differences of the subjects had no obvious effect on the mechanical impedance, but No. 4 subject had two peaks of mechanical impedance amplitude at around 16 Hz and 30 Hz. The second peak may be associated with the resonance frequency of the hand-arm system at this posture and hand force level. Although the differences among individual subjects had certain effects on the mechanical impedance of the hand-arm system in a specific frequency range, the change trend of mechanical impedance amplitude along with the vibration frequency was basically the same for all subjects. According to GB 10000-88 [22], the anthropometric values of the No. 4 subject were closer to the average of Chinese adult males, which were shown in Table 3. Consequently, the test and calculation results of the No. 4 subject were further discussed.

3.2. Effect of Hand-Arm Posture on Mechanical Impedance. Figure 8 shows the changes in the mechanical impedance amplitude of the human hand-arm system with the vibration frequency under different hand-arm postures. Other test conditions are as follows: vibration intensity is $5\,m/s^2$, grip force is 30 N, and push force is 30 N.

Figure 8 clearly shows that when the elbow angle was 180°, the hand-arm system would produce higher mechanical impedance amplitudes at lower frequencies (below 40 Hz), and when the frequency was extremely low, the hand-arm system exhibited similar characteristics to dampers. Under this combination of grip and push force levels, the peak value of the mechanical impedance amplitude occurred at a frequency of around 20 Hz. When the elbow angle was 90°, the peak value of mechanical impedance amplitude appeared at around 41 Hz. Aldien et al. have reported that the frequency corresponding to the peak value of the mechanical impedance amplitude is usually related to the main resonance frequency of the hand-arm system [21]. When the elbow angle was 90°, the frequency corresponding to the peak value of the mechanical impedance was in good agreement with the range of resonance frequency values of the hand-arm system reported in many studies [23]. When

Table 3: The average anthropometric values of Chinese adult males.

Main parameter	Weight (kg)	Height (cm)	Length of Hand (cm)	Width of Hand (mm)	Length of upper Arm (cm)	Length of Forearm (cm)
Average values	59.0	167.8	18.3	82.0	31.3	42.0

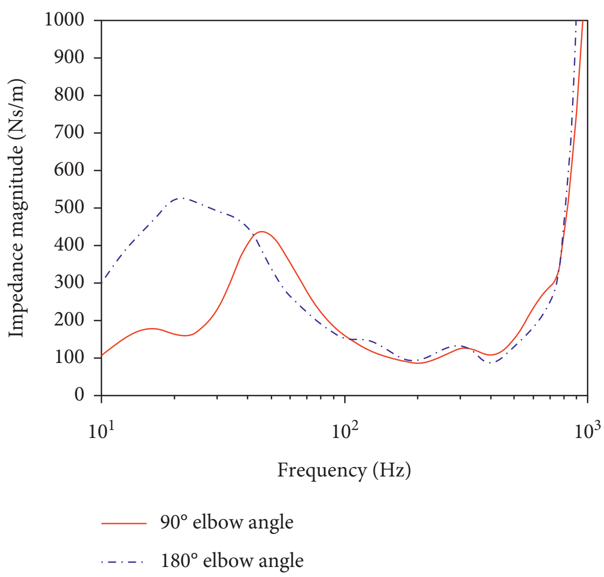


Figure 8: Amplitude of mechanical impedance of the hand-arm system under different postures (5 m/s^2 vibration magnitude, 30 N grip force, and 30 N push force).

the frequency ranged from 40 to 100 Hz and the elbow angle was 90°, the mechanical impedance amplitude of the hand-arm system was higher; when the frequency was higher than 100 Hz, the hand-arm posture had no obvious effect on the mechanical impedance.

When the frequency was low and the elbow angle was 180°, the system produced a significantly higher mechanical impedance amplitude, indicating a relatively high effective mass of the coupling of the hand-arm system with the vibrating handle, which would cause the flow of low-frequency vibration energy to the whole body through the hand-arm system. Compared with the resonance frequency of the hand-arm system with an elbow angle of 90°, a higher effective mass would bring a lower resonance frequency.

3.3. Effect of Grip Force on Mechanical Impedance. Figure 9 shows the effect of grip force on the mechanical impedance of the hand-arm system under different hand-arm postures when the vibration intensity was 5 m/s^2 and the push force was 30 N.

Figure 9 shows that, in two different hand-arm postures, an increase in grip force would increase the frequency corresponding to the peak value of mechanical impedance amplitude of the hand-arm system. When the elbow angle was 90° and the frequency was low (<34 Hz), grip force had no obvious effect on the mechanical impedance of the hand-arm system. When the frequency range was 34–400 Hz, the mechanical impedance amplitude of the hand-arm system increased with greater grip force; however, when the frequency was further increased, the effect of grip force was reduced. For the hand-arm posture with an elbow angle of 180°, when the frequency was low, the mechanical impedance amplitude was significantly higher, indicating that the hand-arm system was more strongly coupled to the vibrating handle. In almost the entire frequency range studied, a higher grip force usually corresponded to a higher mechanical impedance amplitude, but with the increases in frequency, the impact of grip force on the mechanical impedance of the hand-arm system would be gradually weakened. These findings are in good agreement with those of Aldien et al. [21].

3.4. Effect of Push Force on Mechanical Impedance. Figure 10 shows the effect of changes in push force on the mechanical impedance under the two hand-arm postures when the vibration intensity was 5 m/s^2 and the grip force was 30 N.

It can be seen that, similar to the effect of grip force, an increase in push force would also increase the frequency corresponding to the peak value of mechanical impedance amplitude of the hand-arm system under both hand-arm postures. When the elbow angle was 90° and the frequency ranged from 30 Hz to 200 Hz, an increase in push force also increased the mechanical impedance amplitude of the hand-arm system, but when the frequency was below 30 Hz or above 200 Hz, the effect of push force on the mechanical impedance of the hand-arm system was weakened. When the elbow angle was 180°, an increase in push force would elevate the mechanical impedance amplitude of the hand-arm system in almost the entire frequency range, particularly at lower frequencies (<100 Hz).

3.5. Effect of Vibration Intensity on Mechanical Impedance. Figure 11 shows the effects of different vibration intensities on the mechanical impedance of the hand-arm system under two hand-arm postures when the grip force was 30 N and the push force was 30 N.

For different vibration intensities, the variations of the mechanical impedance amplitude of the hand-arm system were basically consistent under the two hand-arm postures. When the frequency was lower (<140 Hz), vibration intensity had a greater impact on the mechanical impedance under the hand-arm posture with an elbow angle of 180°, which is consistent with the results of Aldien et al. [21]. In addition, under this posture, the mechanical impedance amplitude decreased with increasing vibration intensity. Lundström et al. also found that when the frequency was below 100 Hz, the mechanical impedance amplitude of the hand-arm system decreased with increasing vibration intensity, indicating the reliability of the measurement in this study [7].

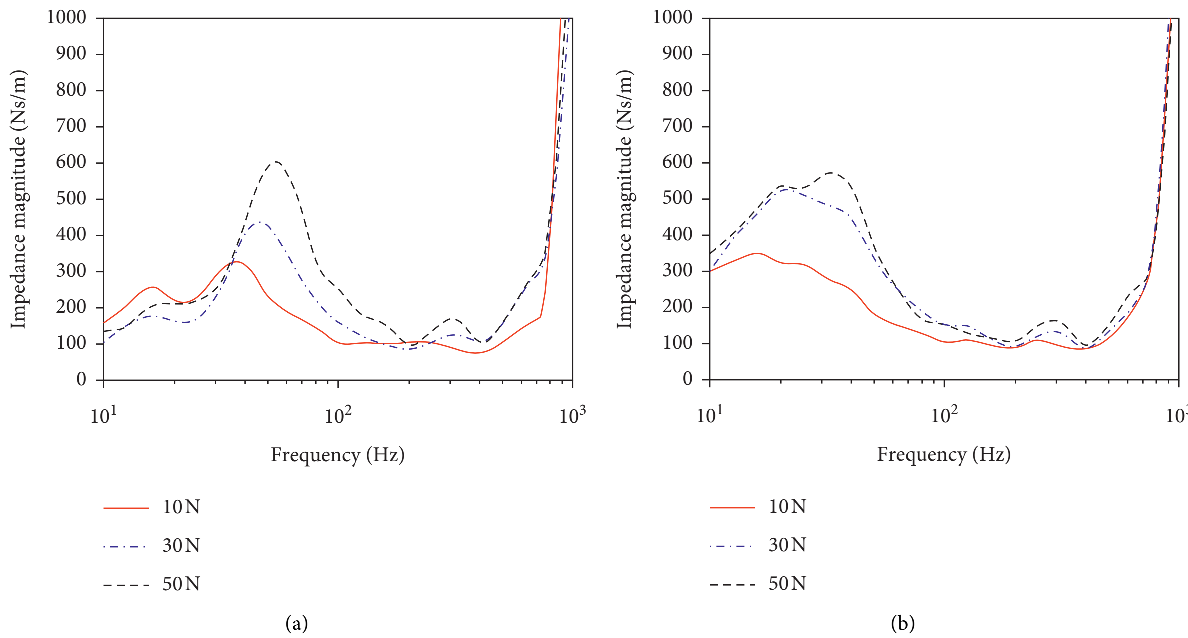


FIGURE 9: Amplitude of mechanical impedance of the hand-arm system under different grip forces (5 m/s^2 vibration magnitude and 30 N push force). (a) 90° elbow angle. (b) 180° elbow angle.

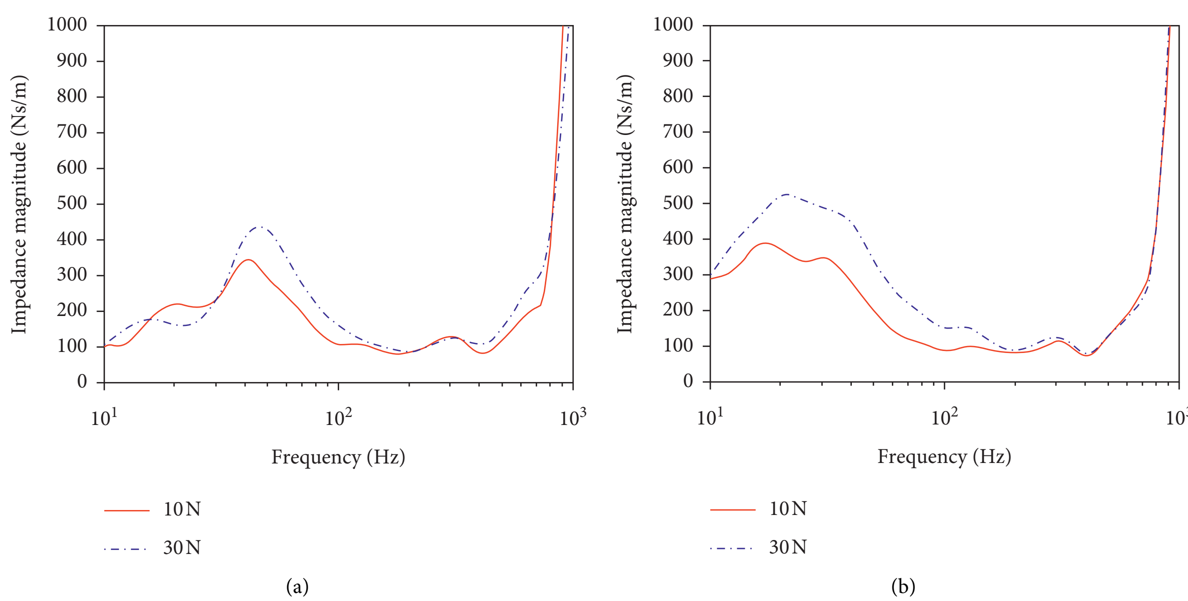


FIGURE 10: Amplitude of mechanical impedance of the hand-arm system under different push forces (5 m/s^2 vibration magnitude and 30 N grip force). (a) 90° elbow angle. (b) 180° elbow angle.

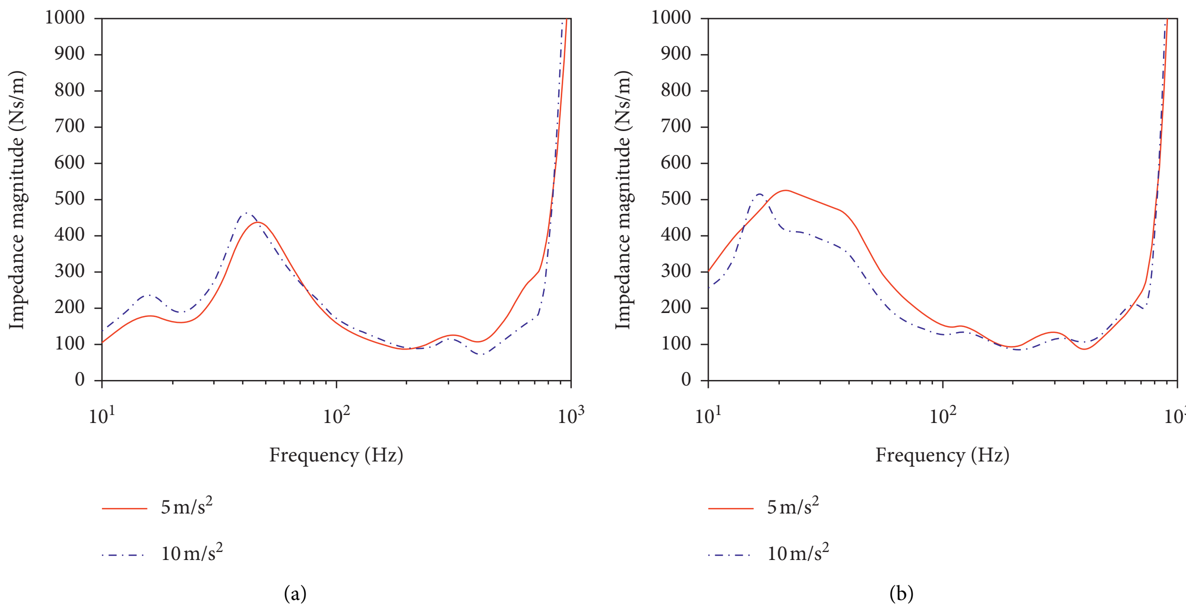


Figure 11: Amplitude of mechanical impedance of the hand-arm system under different vibration magnitude (30 N grip force and 30 N push force). (a) 90° elbow angle. (b) 180° elbow angle.

4. Conclusion

To investigate the effects of hand-arm posture, grip force, push force, and vibration excitation intensity on the mechanical impedance of human hand-arm system, a test system with a self-developed vibration handle has been established. On the basis of the testing system, the mechanical impedance of the right-hand-arm system of seven healthy adult males were tested and calculated under different hand-arm postures, vibration intensities, grip forces, and push forces. At the same time, taking the No. 4 subject as the research object, the influence of different test factors on the mechanical impedance of the human hand-arm system was discussed.

In conclusion, increases in grip or push force contribute to higher mechanical impedance amplitudes and frequencies corresponding to the peak value of the mechanical impedance. Vibration intensity greatly affects the mechanical impedance amplitude in a lower frequency range when the elbow angle is 180°. The investigation of the mechanical impedance of the hand-arm system will help to optimize and develop the biomechanical model of the human hand-arm system. In addition, since the influence of different factors on the mechanical impedance of the hand-arm system was analyzed within a certain frequency range, the injury of the human arm can be more accurately targeted, which is beneficial to the development of vibration isolators.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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