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Experimental Investigation of Damping and Mass Parameters of an Adjustable Physical Hand-Arm Model for Reproducing Human Mechanical Impedance

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ABSTRACT

Hand-arm models enable reproducible investigation of physically coupled human-machine systems. They can substitute for the human user in experimental investigations by mechanically representing the human hand-arm system. This enables the dynamic interaction between the hand-arm system and an actual machine to be studied under controlled, reproducible, and systematically variable conditions. Adjustable hand-arm models also make it possible to represent different anthropometric characteristics and force combinations. Many existing models are either nonadjustable or show deviations from mechanical impedance responses measured in humans, particularly in the frequency range from 350 to 500 Hz. The adjustable hand-arm model investigated here is implemented as a three-mass oscillator. To address the observed deviations, two studies were conducted using the adjustable hand-arm model. In the first study, the damping behavior of the three-mass oscillator was systematically investigated. In the second study, the mass parameters of the adjustable three-mass hand-arm model were systematically varied and adapted to the measured impedance responses of the human hand-arm system. Based on these investigations, an enhanced adjustable physical hand-arm model with adapted damping and mass parameters was developed to achieve closer agreement with the measured mechanical impedance of the human hand-arm system over the investigated frequency range from 10 to 500 Hz. The new hand-arm model provides an adjustable physical representation whose damping and mass parameters are specifically adapted to the measured mechanical impedance of the human hand-arm system over the frequency range from 10 to 500 Hz. The investigated parameterization therefore, represents a frequency-dependent trade-off rather than a uniform improvement over the entire frequency range.

Keywords: Human machine interaction, Hand-arm-model, Mechanical impedance, Modeling, Industry 5.0, Dynamic load

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INTRODUCTION

In science and industry, there is an approach that involves modeling the behavior of the human hand-arm system using equivalent systems, such as multi-mass oscillators. These so-called physical hand-arm models enable the investigation of physically coupled human-machine systems under reproducible, controlled, and systematically variable boundary conditions. These models do not reproduce the complete anatomy of the human hand-arm system; rather, they represent the passive biodynamic properties that are relevant to human-machine interaction. In this way, the influence of the human operator on the dynamic behavior of hand-held machines can be incorporated into repeatable test-bench experiments (Lindenmann et al., 2021).

In hand-arm vibration research, the mechanical impedance at the driving point is commonly used to characterize the dynamic behavior of the human hand-arm system. Mechanical impedance is defined as the complex, frequency-dependent ratio of the applied force $F(\omega)$ to the resulting vibration velocity $v(\omega)$:

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

Mechanical impedance can be described by its magnitude and phase and characterizes the dynamic properties of the hand-arm system at the hand-handle interface. To compare a physical hand-arm model with the human hand-arm system, both systems must be investigated under comparable excitation and boundary conditions. The objective is for the physical model to reproduce, as functionally equivalently as possible, the range of human mechanical impedance relevant to the intended application (Zhang et al., 2021).

However, the mechanical impedance of the human hand-arm system is not constant. It is influenced by factors including grip force, push force, body and arm posture, frequency, excitation direction, and the anthropometric characteristics of the test subject. Consequently, mechanical impedance measurements in humans exhibit both interindividual variability and variability resulting from the experimental conditions. A physical model with fixed mechanical parameters can therefore generally represent only a specific combination of user population, body posture, interaction forces, and application scenario (Lindenmann et al., 2022). Earlier physical models, such as the axial hand-arm model developed by Cronjäger et al. (1984), were designed for specific applications, including the testing of hammer drills. Subsequent research identified the need for adjustable mechanical impedance elements that allow different user and application conditions to be represented using a single model (Cronjäger et al., 1984; Bruchmüller et al., 2015). In 2023, Lindenmann developed an adjustable physical hand-arm model for translational vibration excitation along the zh-axis of the basicentric coordinate system of ISO5349-1. The model incorporates independently adjustable stiffness and damping elements as well as an adaptable handle interface. These features allow different dynamic properties of the human hand-arm system to be represented. The model can support static forces of up to 180 N; however, the investigation demonstrates that the model reproduces the mechanical impedance of the human hand-arm system only up to an excitation frequency of 200 Hz (Lindenmann, 2023).

The dissertation does not demonstrate sufficient agreement between the model and the mechanical impedance measured in humans for frequencies from 10 to 20 Hz and above 200 Hz, as shown in Figure 1. Preliminary investigations show deviations, particularly in the 350-500 Hz frequency range. Analysis of the existing model indicates that the deviations at higher frequencies cannot be sufficiently compensated by the available stiffness adjustment and are primarily associated with the damping and inertial properties of the model, which leads to the following research question:

How should the damping and mass parameters of an adjustable physical hand-arm model be designed to reproduce the mechanical impedance of the human hand-arm system under application-relevant grip and push forces over the frequency range from 10 to 500 Hz?

To answer this question, we used the Institute of Product Engineering (IPEK) hand-arm model (IPEK HAML) according to Lindenmann as the base system and mathematically described it as a mass-spring-damper model with three degrees of freedom. In this paper two systematic experimental studies were conducted at the Karlsruhe Institute of Technology (KIT)'s interaction test rig (Lindenmann et al., 2021). The first study varied the model's damping parameters (d1) to analyze their influence on the frequency response to vibration. The second study systematically adjusted the masses (m1) of the three oscillating subsystems to investigate their effect on mechanical impedance.

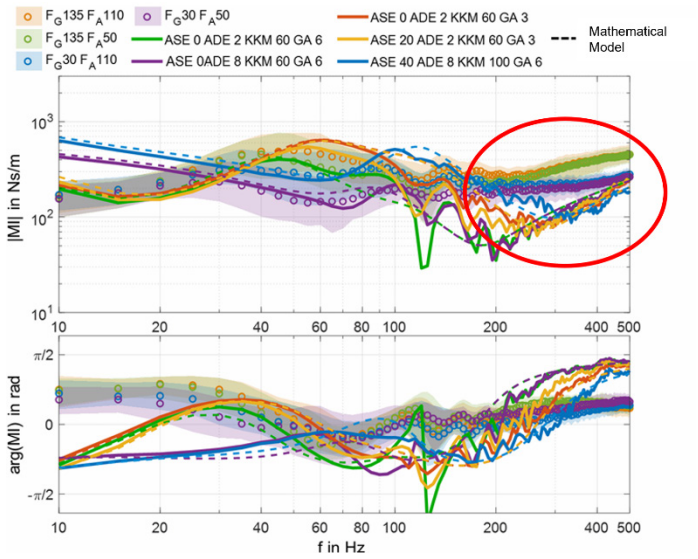


Figure 1: Upper plot: Mechanical impedance as a function of frequency for the human hand-arm system (dotted line) and the IPEK Hand-Arm Model according to Lindenmann (solid line). The red circle highlights the deviation between the two impedance curves in the high-frequency range. Lower plot: Corresponding phase response of the human hand-arm system and the IPEK Hand-Arm Model as a function of frequency.

METHODS

The methodological approach is divided into three subsections. First, the experimental setup and the integrated sensor system are described. Subsequently, the hand-arm model used in this study and its mathematical

representation are introduced. Based on this, the experimental procedure is presented, followed by a description of the parameters varied during the experiments.

Experimental Setup

The experiments were conducted at the interaction test bench at KIT. The test bench consists of two shaker systems mounted on an adjustable portal frame. For the experiments presented in this study, the portal frame was configured as shown in Figure 2. The axial shaker was oriented such that its principal axis, and therefore the excitation direction, pointed toward the floor. In Figure 2, this excitation axis is indicated by the arrow labeled. A measurement handle designed in accordance with ISO 10819 was mounted on the axis of the interaction test bench (DIN, 2001). The handle is equipped with two uniaxial accelerometers (type 356A15, PCB Piezotronics GmbH, Hückelhoven, Germany) (sensor 2 in Figure 2) which were mounted at the top and bottom of the cylindrical handle to capture translational acceleration. Two triaxial force sensors (sensors 1 in Figure 2) (type 9027C, Kistler Instruments AG, Winterthur, Switzerland) were mounted at the interface between the hand and the handle to measure the push force. Two uniaxial force sensors (sensors 3 in Figure 2) (type 9011A, Kistler Instruments, Winterthur, Switzerland) were integrated within the split cylindrical handle, to measure the grip force. The measurement handle was calibrated according to the calibration method proposed by Heyden et al. (2021), which is based on the method described by Dong et al. (2006). Prior to each measurement, all sensors were zeroed to reduce the influence of sensor drift. Measurement data were acquired and processed using an ADwin-II real-time measurement system.

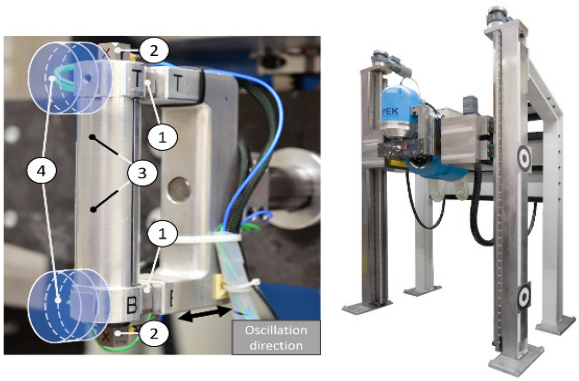


Figure 2: Left: ISO 5349-compliant measurement handle equipped with two accelerometers (2), two uniaxial force sensors integrated into the handle shell for measuring grip force (3), and two triaxial force sensors for measuring push force (1). The blue-shaded region (4) indicates the calibration mass. Right: Height-adjustable and tiltable interaction test bench equipped with the axial shaker. Figures adapted from Lindenmann et al. (2022).

Hand-Arm Model

The IPEK HAML served as the basis of this study. The IPEK HAML is an adjustable physical hand-arm model. Its underlying model representation is shown in Figure 3 and corresponds to a three-degree-of-freedom mass-spring-damper system with three masses.

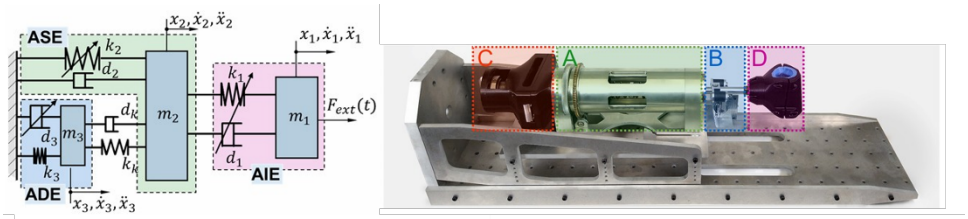


Figure 3: IPEK Hand-Arm Model according to Lindenmann (2023). Left: Schematic representation of the model as a three-mass system. Right: Adjustable physical hand-arm model consisting of (A) the constant-force mechanism, (B) the adjustable stiffness assembly, (C) the adjustable damping mechanism, and (D) the adjustable handle interface.

Based on the model parameters, the mechanical impedance can be determined according to Equation 2. The derivation can be found in Spengler's article (Spengler et al., 2025).

$$MI(i\omega) = \frac{F_{ext}(i\omega)}{\dot{X}_1(i\omega)}$$

$$= m_1 i\omega + d_1 + \frac{k_1}{i\omega} - \frac{\left(d_1 + \frac{k_1}{i\omega}\right)^2 \left(m_3 i\omega + d_3 + d_k + \frac{k_3 + k_k}{i\omega}\right)}{\left(m_2 i\omega + d_1 + d_2 + d_k + \frac{k_1 + k_2 + k_k}{i\omega}\right)\left(m_3 i\omega + d_3 + d_k + \frac{k_3 + k_k}{i\omega}\right) - \left(d_k + \frac{k_k}{i\omega}\right)^2} \quad (2)$$

In the present experiments, mechanical impedance is used as a calculated measurement quantity and is determined according to Equation 1. This quantity is used to characterize the dynamic behavior of the three-mass system. The model consists of four elements, as illustrated in Figure 3. Elements A, B, and D represent the three components of the three-mass system. Element A consists of two anthropometrically arranged springs whose properties can be adjusted (Lindenmann et al., 2022).

Previous model analysis indicate that d1 and m1 predominantly determine the impedance response of the handle interface in the frequency range in which the deviations occur. The present study focuses on element D, the adjustable handle interface. According to the model representation and the result from Lindenmann (2023), this element particularly affects the behavior of the mechanical impedance at high frequencies as well as the corresponding phase

response. Therefore, the investigation is limited to this part of the hand-arm model. In the IPEK HAML, the adjustable handle interface consists of a front and a rear half-shell filled with silicone with a Shore 00 hardness of 20. The silicone core was cast around a casting core. The further development of this adjustable handle interface is described in the following section.

Experimental Procedure

All measurements in this study were performed in triplicate. For subsequent analysis, the three repeated measurements for each configuration were combined by calculating their arithmetic mean. Excitation was applied using a multisine signal over the frequency range from 10 to 500 Hz with a frequency resolution of 5 Hz. In the first part of the study, the damping characteristics of the handle interface shown in Figure 4 were systematically investigated. For this purpose, a new handle shell was developed that allows damping elements to be positioned at several predefined locations. The investigated positions are indicated by red circles in Figure 4. Sorbothane elements with three different hardness levels were evaluated as damping materials: Duro 30, Duro 50, and Duro 70. In addition to hardness, the number of damping elements was varied. For this purpose, one to three semicircular Sorbothane elements were installed per handle shell. Furthermore, the influence of element geometry was investigated by comparing semicircular Sorbothane elements with strip-shaped elements. Based on the evaluation of this experimental series, a damping configuration for d1 was selected. While maintaining this configuration, the influence of mass m1 was subsequently investigated. For this purpose, m1 varied from 0 to 180 g. As shown in Figure 4, the additional mass was attached directly to the measurement handle. This experimental series was also performed in triplicate for each investigated mass configuration. Excitation was again applied using a multisine signal over the frequency range from 10 to 500 Hz with a frequency resolution of 5 Hz.

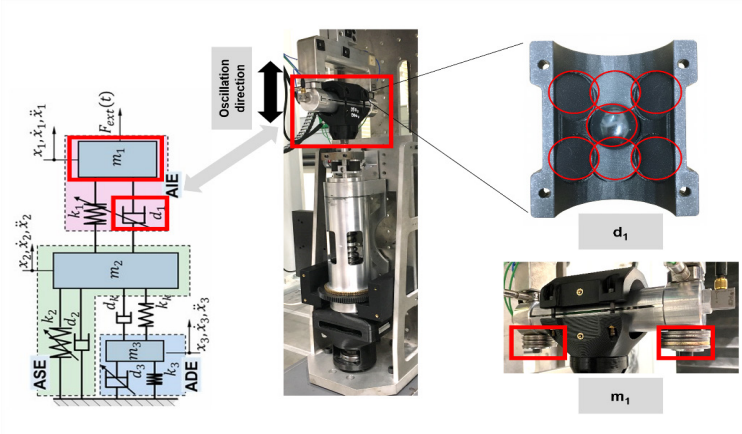


Figure 4: IPEK Hand-Arm Model according to Lindenmann (2023) with the modified adjustable handle interface mounted beneath the interaction test bench. The detailed view shows the adjustable damping element (d1) and mass (m1).

RESULTS

The systematic variation of the damping element d1 resulted in a change in the range of mechanical impedance that could be adjusted using the physical hand-arm model. As shown in Figure 5, the achievable impedance range was extended toward higher magnitudes, particularly in the frequency range from 200 to 500 Hz.

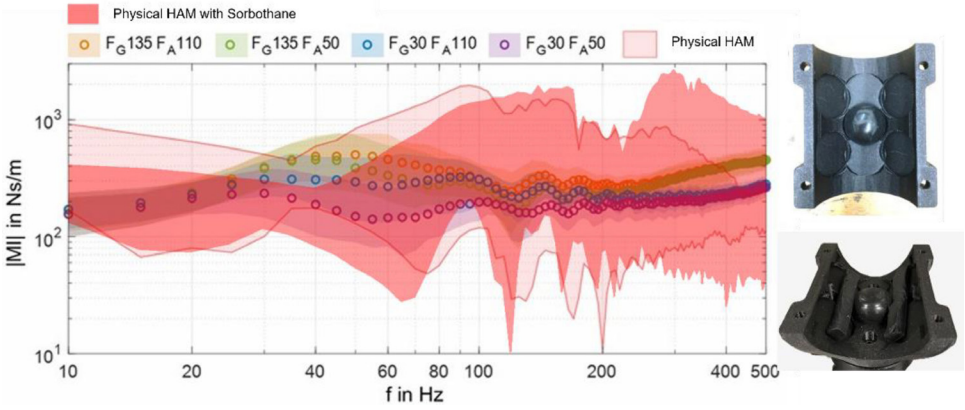


Figure 5: Mechanical impedance as a calculated measurement quantity as a function of frequency. Circular markers represent measurements of the human hand-arm system for different combinations of grip and push forces. The red-shaded area indicates the range of mechanical impedance achieved by the IPEK HAML according to Lindenmann without and with the new results fromt Sorbothane damping elements. On the left the setup up for d1 is shown.

At the same time, agreement with the considered human reference data decreased relative to the previous model configuration in the frequency range from approximately 30 to 60 Hz. Thus, adjustment of d1 resulted in a frequency-dependent shift of the adjustable impedance range. For the subsequent investigation of the influence of m1, the Duro 30 configuration selected based on the damping investigations was retained. On the handle shell facing the system, this configuration consisted of one Duro 30 hemispherical element combined with two thin Duro 30 strips, whereas one Duro 30 semicircular element was used on the handle shell facing away from the system.

While maintaining this damping configuration, m1 was varied from 0 to 180 g. Figures 6 and 7 show two selected configurations. Figure 6 presents the results for m1 = 140 g. The experimentally determined magnitude of the mechanical impedance of the hand-arm model initially exhibits a broad maximum in the mid-frequency range and, following local minima between approximately 120 and 250 Hz, increases again at higher frequencies. Starting at approximately 300 Hz, the intended increase in impedance magnitude resulting from the adjustment of d1 and m1 is observed up to 500 Hz. The mathematical three-mass model captures the overall frequency-dependent trend of the experimentally determined impedance magnitude. Deviations between the experimental measurements and the mathematical model are

particularly evident in the frequency range from approximately 120 to 250 Hz. However, a separate evaluation of the phase reveals substantially larger differences. In particular, above approximately 200 Hz, the phase of both the experimental hand-arm model and the mathematical model increases considerably more strongly than that of the human reference data. At 500 Hz, the phase values of the experimental and mathematical models shown in Figure 6 are approximately 1.0 to 1.3 rad, whereas the human reference phase is approximately 0.2 rad. Agreement in impedance magnitude should therefore not be interpreted as corresponding agreement in the complete complex mechanical impedance. Figure 7 shows another investigated configuration with m1=153 g. For this configuration, the experimentally determined impedance magnitude likewise increases again toward higher frequencies after reaching a minimum in the mid-frequency range. The mathematically calculated response also captures the overall shape of the measured impedance magnitude, although local deviations are particularly apparent between approximately 150 and 300 Hz. Similar to Figure 6, the phase shows greater deviations from the human reference data above approximately 200 to 250 Hz. At 500 Hz, the phase of both the physical and mathematical models again lies clearly above the human reference phase. The two configurations presented therefore demonstrate that variation of the damping configuration d1, in combination with adjustment of the mass parameters, enables a targeted increase in the magnitude of the mechanical impedance in the high-frequency range.

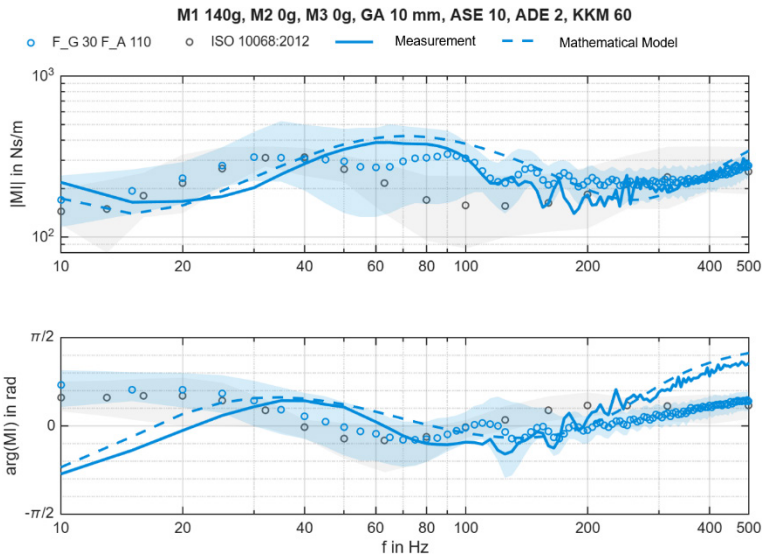


Figure 6: Comparison of mechanical impedance as a calculated measurement quantity as a function of frequency for the human hand-arm system (markers), the mathematical model (dashed line), and the experimentally measured IPEK HAMS (solid line). The IPEK HAMS was configured with Duro 30 Sorbothane hemispheres and a mass of .m1 = 140g.

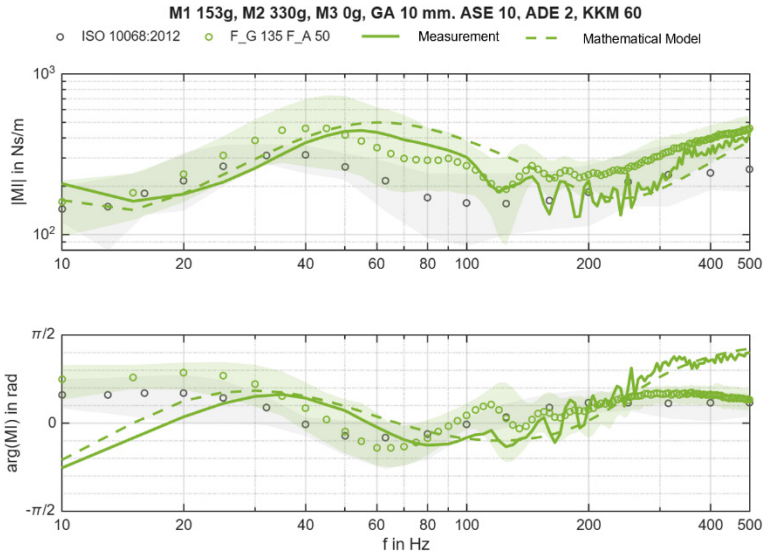


Figure 7: Comparison of mechanical impedance as a calculated measurement quantity as a function of frequency for the human hand-arm system (markers), the mathematical model (dashed line), and the experimentally measured IPEK HAMS (solid line). The IPEK HAMS was configured with Duro 30 Sorbothane hemispheres and a mass of m1 = 153g.

DISCUSSION

The results show that variation of the damping element d1 in combination with adjustment of the mass parameters enables targeted modification of the mechanical impedance of the physical hand-arm model, particularly at high frequencies. Previous investigations demonstrated that the mechanical impedance of the human hand-arm system depends on grip and push force over the frequency range from 10 to 500 Hz (Lindenmann et al., 2022). Based on these human reference data, the adjustable physical IPEK HAML was developed to represent different mechanical impedance characteristics, but its validated application range was limited to excitation frequencies up to 200 Hz (Lindenmann, 2023). The present results extend this previous work by showing that modification of d1 and the mass parameters shifts the achievable impedance range toward higher magnitudes between approximately 200 and 500 Hz. However, this extension is accompanied by reduced agreement with the human reference data between approximately 30 and 60 Hz. The investigated parameterization therefore, represents a frequency-dependent trade-off rather than a uniform improvement over the entire frequency range. In addition, agreement differs between the magnitude and phase of the mechanical impedance, with larger deviations in phase occurring particularly at higher frequencies. The investigated Sorbothane configurations further characterize the range over which the mechanical impedance can be adjusted by modifying d1. However, the present study investigated the Sorbothane configurations and mass parameters only for individual grip and push force conditions. Such a relationship would require a systematic comparison using a defined quantitative measure of agreement. Based on these findings, the IPEK HAML was further developed into the

IPEK Hand-Arm Model Saurbier (IPEK HAMS). Compared with the previous configuration, the modified handle interface provides greater flexibility for adjusting the mechanical impedance in the high-frequency range, while the reduced agreement at lower frequencies must be considered when selecting the model parameterization. Future investigations should therefore quantify this trade-off and evaluate the model under time-varying force conditions.

LIMITATION

In this study, the influence of mass (m1) and damping (d1) on the dynamic behavior of the IPEK Hand-Arm Model Lindenmann was systematically investigated. First, the model was parameterized using previously investigated settings to identify potential changes relative to earlier investigations. Subsequently, the effects of (m1) and (d1) were investigated independently. Each measurement was repeated three times. As a result, the measurement accuracy of the entire setup is subject to a non-negligible degree of inaccuracy. A further limitation is the potential aging of the springs and Sorbothane materials used in the model. Changes in their mechanical properties may affect the mechanical impedance as a calculated measurement quantity and, consequently, the experimental results. The influence of such aging effects was not investigated separately in the present study and should therefore be addressed in future research. In addition, further investigations should take into account the focus on mechanical impedance in relation to phase, as well as the limited force levels.

CONCLUSION

The present study systematically investigates the influence of mass (m1) and damping (d1) on the mechanical impedance as a calculated measurement quantity of the IPEK Hand-Arm Model. The extended adjustment range does not result in uniform agreement with human mechanical impedance over the entire frequency range, particularly with respect to the phase response at higher frequencies. The results demonstrate that targeted variation of both parameters can influence the impedance profile, particularly at high frequencies. Based on these findings, the adjustable handle interface was further developed and implemented in the IPEK HAMS. The developed solution extends the adjustment capabilities of the physical hand-arm model and enables more targeted parameterization of the mechanical impedance as a calculated measurement quantity. The study therefore provides a basis for further investigations, particularly with respect to reproducing time-varying loading conditions and force profiles.

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Declaration of Generative AI and AI-assisted Technologies in the Writing Process

To prepare this paper, the authors used the Deepl SE, Copilot and ChatGPT tools to enhance their writing and language skills. Having used these tools, the authors then reviewed and revised the content as necessary and take full responsibility for the content of this publication.

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