Modeling of the human hand using 3D multi-body models for simulative vibration studies

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Abstract

Modeling the human hand-arm system in dynamic simulations is challenging. Current standards provide separate multibody models for different spatial excitation directions. However, it must be assumed that the dynamic behavior of the human hand-arm system is coupled for different excitation directions. Numerical 3D hand-arm models allow the simulation of arm dynamics taking into account possible coupling effects. In current multibody models of the hand-arm system, the human hand is represented in a very simplified way. More sophisticated finite element models usually deal with very specialized aspects of human arm dynamics and cause high computational and modeling efforts. In this paper, we investigate how the human hand can be modeled in multibody simulations. Two types of models are investigated. One type uses a combination of rigid and flexible modally reduced FE bodies, while the other type investigates a rigid-body-only approach. Using experimental data, both models are parameterized and discussed in terms of their suitability for handheld modeling. This work provides the basis for extending and refining existing hand-arm models in the context of the hand.

1. Introduction

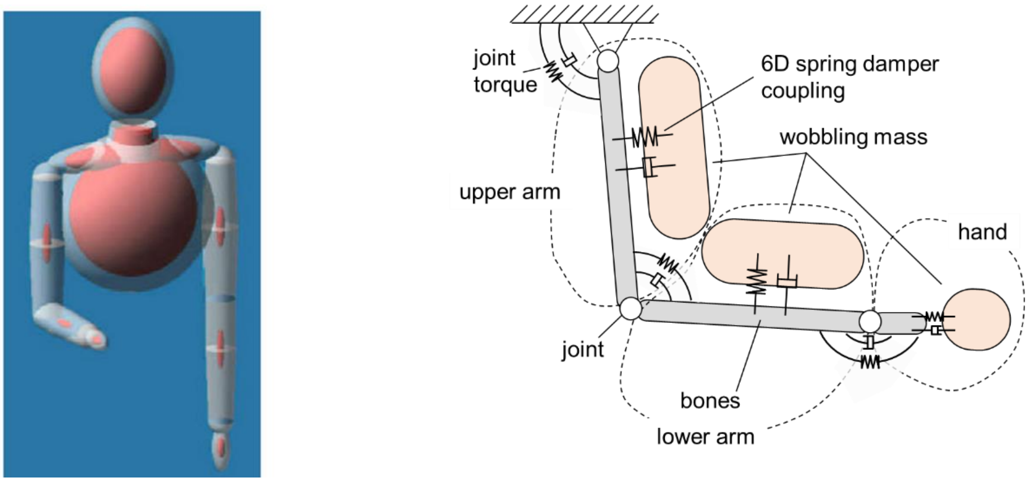
The assessment of vibration is an important step in the development process of hand-held machinery. Hereby, both the function of the technical system and thus the emitted vibration strongly depend on the human interaction. This is a challenge for product development because it is difficult to take the human influence on the technical system into account. This is because the influence on the machine can vary strongly between individual humans or even for a single human. Therefore, a lot of effort must be put into manual testing of the technical system to ensure a reliable and significant experimental result. This also creates a considerable risk for development, as handheld testing can usually only be done once a physical prototype of the machine is available which is usually very late in the development process. With this, the costs of design iterations or (even worse) concept iterations are high.

In the sense of frontloading, it is therefore possible that simulative tests are used to predict the functionality but also the emitted vibration of a device with human interaction. For mechanical interaction of the human hand-arm system with the device in manual work processes, hand-arm models can be used to simulate the human interactions in terms of vibrations.

As a standard, ISO 10068:2012 [1] provides several parametrized 1D mathematical models which represent the hand-arm dynamics with different parameter sets for each spatial direction. These models can be derived from the mechanical impedance of the hand-arm system which is a frequency related quantity that gives insight about the stiffness, damping and inertia properties of the hand-arm system over the excitation frequency.

However, in a recent study, it has been shown that ISO 10068:2012 does not represent the human hand-arm impedance sufficiently [2]. This is because the impedance values of ISO 10068:2012 do not apply to many manual work-related application scenarios in terms of grip force, push force and arm postures. Lindenmann et al. [2] have shown that ISO 10068:2012 does underestimate the human impedance for higher grip force and push force values. As a consequence, the validity of the models in ISO 10068 is questionable. Additionally, in ISO 10068:2012 it is stated, that the individual spatial directions can be handled as independent from each other. Recent studies on a 3D excitation of the hand-arm system, however, suggest that there is a possible cross coupling between the individual spatial directions [3].

More sophisticated models provide a 3D representation of the human hand-arm system. Here it is possible to include geometric properties of the arm into the model. For this, Keppler presented a 3D multibody hand-arm model as shown in Figure 1-a. Figure 1-b shows the basic model structure. The model consists of a bone structure which is interconnected by respective joints (wrist, elbow, shoulder). A respective joint torque which is modelled as a spring damper relationship provides the rotational coupling. Here the forearm bones (ulna and spoke) are simplified as one single bone. The hand structure is also modeled as one single bone mass. For representing the soft tissue dynamics one rigid wobbling mass is coupled to each bone by means of a 6D spring damper relationship (translation and rotation). Here, the hand tissue is also simplified as one single mass. The application of active forces, as for instance push forces, can be realized by controlling the joint torques. With this rigid multibody hand-arm model Keppler was able to fit experimental data on the human hand-arm dynamics well for an excitation along the forearm axis. In a parameter study it was shown that the hand parameters (masses, stiffnesses, damping) have the strongest effect on the obtained results. Keppler [4] (p. 132) also stated that this model may not be sufficiently detailed in terms of hand dynamics and that better results could be obtained with more refined hand models.



a) b)

Figure 1: a) 3D Hand-Arm Modell by Keppler [4] and, b) the structure of the model [based on Keppler [4]]. The model consists of a bone for each limp segment of the human arm. A wobbling mass for each segment represents the inertia properties of the corresponding soft tissues. The wobbling masses are connected to the corresponding bone via a 6D spring-damper relationship.

Adewusi et al.[5] and J. Z. Wu et al. [6] used finite element model (FEM) approaches for the dynamic modeling of the HAS. Adewusi et al. [5] reported a two-dimensional FE analysis for estimating the natural frequencies and natural modes of the human arm. J. Z. Wu et al. [6] presented a three-dimensional model of a single finger on a cylindrical handle. With the help of the parameterized model, conclusions were made about the transmission of vibrations from a vibrating surface to the hand as a function of the gripping force.

Although a FEM approach, if applied correctly, can provide a high quality of simulation results, very high computational costs for transient simulations often limit the applicability of this method since the number of differential equations is very high.

In dynamic simulations of technical systems, the question therefore arises concerning the level of detail of the model.

Concerning the need of a more refined hand model for multibody dynamic simulations as stated by Keppler [4], the research question for this contribution is as follows:

How can a hand model for a multibody hand-arm model be designed, to represent the human hand dynamics?

This paper presents an approach for modelling the human hand in a 3D multibody simulation. The focus of this paper is on the general method and basic considerations.

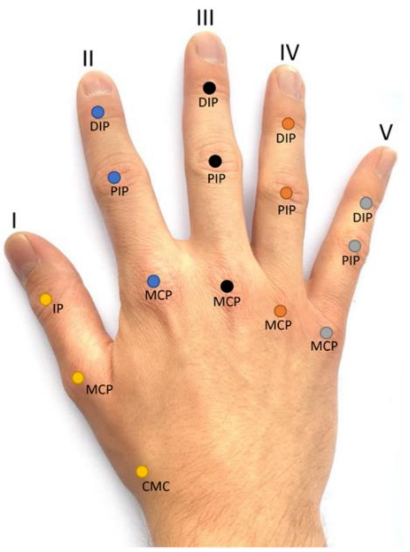
2. Material and Methods

Firstly, this paper presents two different hand models. Each model consists of a multibody structure that models the fingers individually. A preliminary experimental study was conducted on a shaker test bench to measure the hand dynamics. Based on the experimental results, one single finger was parametrized for each model to assess its suitability for future work. The experiment, results, and discussion will focus solely on the middle finger as a basis for future modeling considerations.

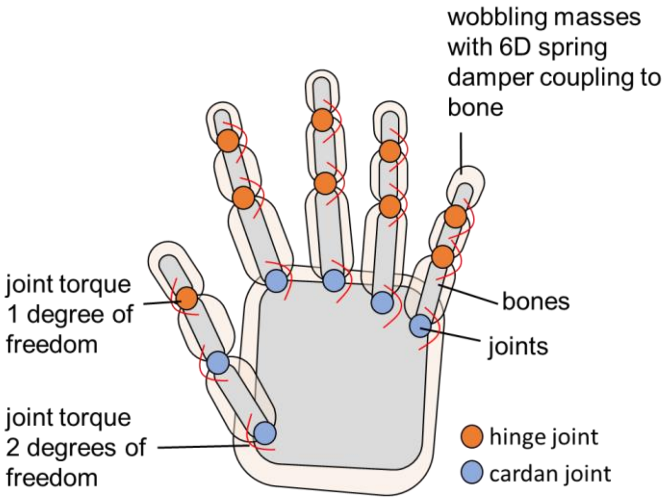
2.1 Hand Models

In the following two different hand models will be presented which both share the same basic structure. While one model follows a pure rigid body model, the second model implements modally reduced flexible bodies to represent the human soft tissue properties.

The general model structure for both hand models is as depicted in Figure *2*. The model consists of a rigid body bone structure which is interconnected by mechanical joints. The finger bones are modelled individually as cylindrical bodies.



a)



b)

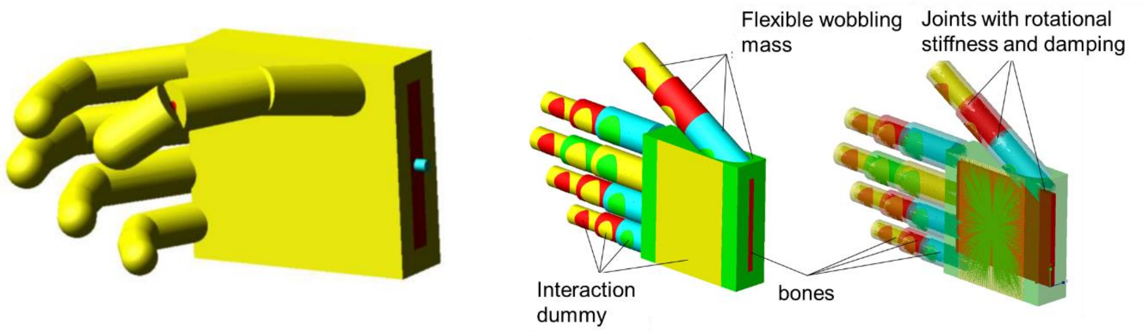
Figure 2: a) Human hand with marked joints; b) the general structure of the hand model. The model consists of a bone structure with one attached wobbling mass for each bone. The fingers and finger segments are modelled individually. The palm and bones of the hand are modeled as one single body with a wobbling mass. The wobbling masses are connected to the corresponding bone via a 6D spring-damper relationship.

In the model the DIP (distal interphalangeal), PIP (proximal interphalangeal) joints of the fingers II to V, and the IP (interphalangeal) joint of the thumb are modelled as hinge joints. The

MCP (metacarpophalangeal) joints of the hand as well as the CMC (Carpometacarpal) joints are modelled as a cardan joint for an approximate representation of the human anatomy. According to the individual degrees of freedom of each joint, joint torques are introduced for each direction of motion which model a viscoelastic behavior. The bones of the hand (excluding the fingers) are modelled as a rectangular single body mass. Each bone is equipped with a respective wobbling mass which is coupled to the bone via a 6D spring-damper coupling (translation and rotation). The finger wobbling masses were modelled as tubes with an inner bore diameter which fits the respective bone diameter.

This model results in thirty-two individual bodies. Regarding the mass, geometry, stiffness, and damping properties of the individual bodies or coupling equations, the model contains 217 parameters which must be fit to the human hand. MSC ADAMS is used as a multibody simulation environment.

Following, two separate model approaches will be examined. Both models are depicted in Figure *3*. First, a purely **rigid body approach** is used for representing the human hand. Second, a multi body hand model with **flexible wobbling masses** is examined.



a) b)

Figure 3: a) Purely rigid body model of the human hand; b). Hand model with flexible wobbling masses. Rigid body interaction dummies were attached to the flexible wobbling mass to enable the interaction with objects.

The wobbling masses are modelled as modally reduced FEM bodies [7]. This reduces the numbers of differential equations compared to a regular FEM implementation but still includes inherent viscoelastic behavior. For this, the body movement is calculated as a linear combination of the eigenmodes of the body. Although this approach only includes linear behavior, we expected that this approach could increase the model quality while keeping the numerical cost low. The conversion of the rigid body to the modally reduced FEM body is conducted with the ADAMS FLEX toolbox. Eigenmodes up to 1500 Hz were included in the evaluation. For practicality of the model, the flexible wobbling masses were equipped with interaction dummies. These are small rigid surface sections that are connected to the wobbling mass. This step is necessary to enable the interaction with separate objects (surfaces, forces) since the point of force application or interaction must be known on the flexible body element before conversion in ADAMS FLEX. The mass properties of the interaction dummies are proportional to that of the wobbling mass. The size of the interaction dummies for the flexible model was estimated by coloring the fingers and palm of the hand and gripping a cylindrical surface. The colored area of the cylindrical surface was then measured in terms of geometry and then transferred to the interaction dummy geometry.

The **stiffness- and damping parameters** have been partially determined in this study by means of a parameter study. Here the parameters for the middle finger were determined by comparing a simulated finger mechanical impedance to measurements. Identifying the parameters was conducted by iteratively adjusting the model parameters manually until a good model fit was observed.

2.2 Experimental Measurements

As a reference for the model parametrization, a preliminary study was conducted on two male subjects (age: 28 & 29 years, weight: 73 and 102 kg, height: 173 and 190 cm). The aim of this experiment was not to provide definite and statistically sound data but to provide a dataset where we could evaluate the model approach. For future work, more experimental data is therefore mandatory.

The experiment aimed on determining the mechanical impedance of the fingers and palm of the hand for a gripping action. While we measured the impedance for all fingers of the hand and the palm, only the method and results for the middle finger will be shown.

For the measurement of the finger mechanical impedance, a vibration excitation of the finger was performed with simultaneous measurement of the excitation force and acceleration. For this purpose, we used an electromechanical shaker (M124M; ETS Solutions Europe; Germany). The shaker is part of a test rig for axial and angular vibration generation, again published by Matthiesen et al. [9]. The shaker is mounted in a carrier mechanism that allows the adjustment of the height above ground.

The shaker assembly was equipped with a measuring handle. This measuring handle meets the requirements of DIN EN ISO 10819:2019 [10]. The handle diameter is 40 mm. Two force sensors (9027C; Kistler Instrumente AG; Switzerland) are used to record the dynamic and static axial forces. Two accelerometers (PCB 356A15; PCB Piezotronics; USA) were used in our setup. In this experiment, signal quality could thus be improved by averaging both acceleration signals. Two force sensors between the two half-shells of the measuring handle (9011A; Kistler Instrumente AG; Switzerland) allow the measurement of the gripping forces.

An ADwin Pro II measuring system (Jäger Computergesteuerte Messtechnik GmbH; Lorsch; Germany) was used to record all signals. A graphical display of the instantaneous gripping forces allowed the subjects to regulate the specified interaction forces. The display of the acting forces was taken unchanged from Mangold [11] (p. 92).

For measuring the finger impedance in a grip-like hand posture, the subjects were seated comfortably in front of the shaker. The forearm was resting on a table. The subjects had to grasp the measurement handle. For determining the finger impedance of the middle finger, the subjects had to lift the remaining fingers and the palm from the handle surface such that only the middle finger remained in contact. For this study, the subjects had to apply a pulling force of 10 N with the middle finger, which, in this configuration, corresponds to the force direction of a typical gripping action.

The experimental setup for measuring the finger impedance is depicted in Figure *4*.

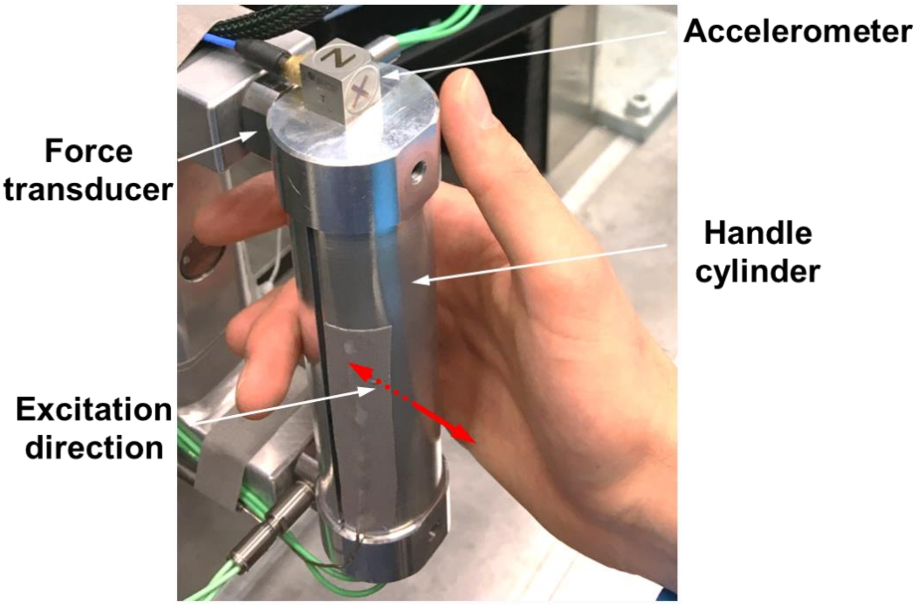


Figure 4: Measurement setup for the determination of the finger impedance. A measurement handle is gripped by the middle finger only. The static pulling force is displayed on a monitor. The hand posture is such that only the middle finger interacts with the handle in a hook like configuration. The remaining fingers are slightly lifted from the handle.

The finger was excited with a multisine excitation signal in the frequency range of 10-500 Hz in a 5 Hz interval for 15 seconds. Each measurement was repeated three times. Data evaluation was conducted in MATLAB according to the method as described in [2]. Here the force and acceleration signals are decomposed into their individual frequency components. Subsequently the raw mechanical impedance is derived from the data. The inherent impedance of the handle and measurement errors were corrected in a subsequent step according to the method by Heyden et al. [12].

2.3 Simulation Study

For the simulation study the setup of the experimental measurements is replicated in the software ADAMS (see. Figure *5*). Only the middle finger is included in the simulation. Here both model types are examined individually using the same method. The middle finger is connected to a coupling dummy via the MCP joint (cardan joint; see Figure *2*) and the respective spring-damper joint torques. The coupling dummy has no mass and is connected to ground via a 3D spring-damper coupling. This resembles the viscoelastic behavior of the remaining hand and arm. The finger is configured in a similar pose as in the experimental measurements. For stable simulation the middle phalanx is rigidly connected to the handle. The proximal and distal phalanx interact with the handle by means of a stiff surface contact definition.

The handle can only move linearly and has no inertia which is only kinematically reasonable since the handle is rigidly fixed to the middle phalanx. A preload of 10 N is applied to the handle in direction of the finger. By applying a dynamic force of 1 N with a subsequently increasing frequency in the range of 10-500 Hz in1 Hz steps, the mechanical impedance is measured at the handle. The simulation setup is depicted in Figure *5*.

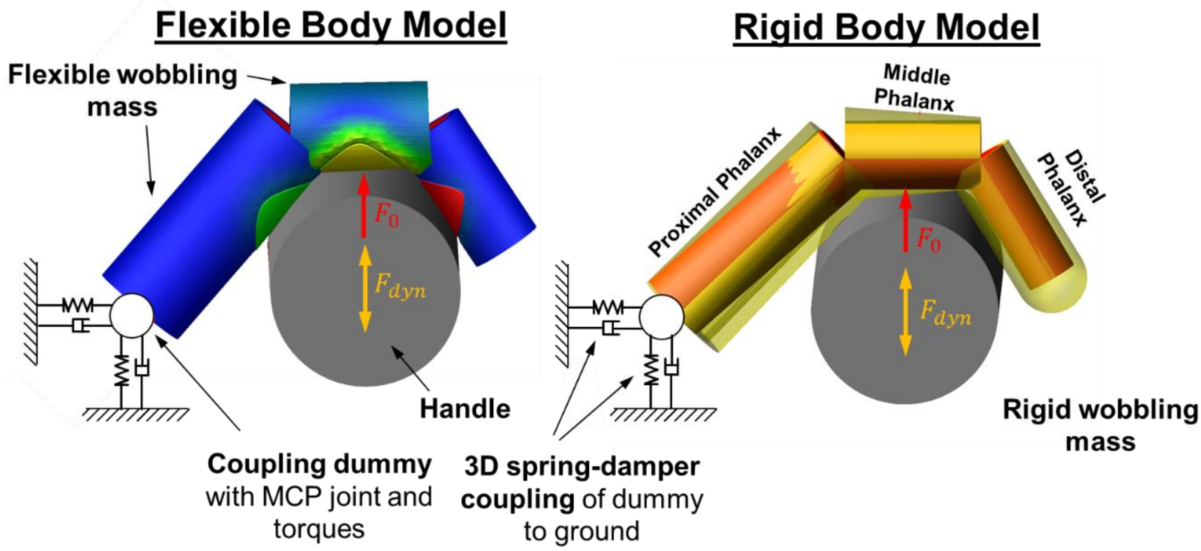


Figure 5: Simulation setup for determining the mechanical impedance of the middle finger. The finger is connected to a coupling dummy body via the MCP joint. The coupling dummy cannot rotate and is connected to ground via a 3D spring-damper relationship. A contact is defined between the handle and interacting finger bodies. The finger is preloaded with a static force of $F_0 = 10\,N$. A dynamic force in the range of 10-500 Hz with an amplitude of $F_{dyn} = 1\,N$ excites the finger model.

3. Results and Discussion

In terms of model generation, it can be stated that the generation of the flexible body model is more time and resource consuming than the rigid body model. A scripted model generation of the flexible body model could not be implemented in the given software at the present time. Although being designed as fully parametrized, the adjustment of the material or geometry properties of the flexible wobbling mass requires the manual generation of the modally reduced body. The generation of the rigid body model can be fully automated, requiring only initial effort. In terms of the measurement and simulation results, Figure *6* shows the mechanical impedance of the human middle finger as modulus and phase over the excitation frequency. The impedance of the finger is represented by a minimum, mean and maximum curve. The corresponding results from the multibody simulation models (flexible and rigid) are shown.

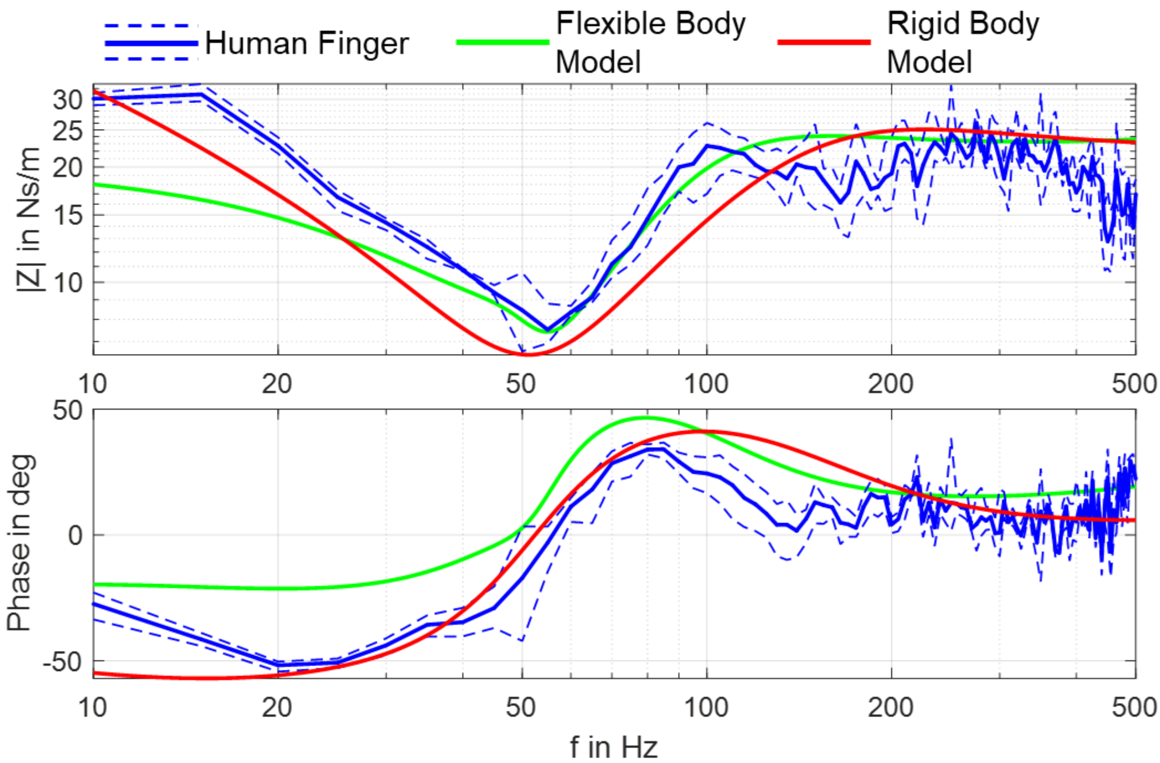


Figure 6: Experimental and simulation results of the mechanical impedance of the human middle finger.

Regarding the mechanical impedance of the finger the magnitude and phase indicate a combined spring damper behavior in the range of approximately 10-50 Hz [13]. This seems reasonable if the finger pivots around its MCP joint in that frequency range. Regarding the DIP and PIP joint no movement is to be expected as all finger segments are in contact with the handle cylinder. At 50 Hz the impedance magnitude is minimal which can be interpreted as a resonance. In the range of approximately 50-100 Hz the magnitude and phase angle increase which indicates a behavior dominated by mass. Above approximately 100 Hz the magnitude stays at an almost constant level and the phase angle decreases to approximately zero which represents a mostly damping dominated behavior.

Both simulation models are able to represent the human finger impedance closely. For the flexible body model, the impedance in the lower frequency region below 50 Hz is underestimated. After the resonance frequency of about 50 Hz the flexible body model represents the human finger impedance very well in both magnitude and phase angle. Since the flexible body model's generation could not be automated, no better parameter fit could be found at the given time for the frequencies below 50 Hz.

The rigid body model provides a closer representation in the lower frequency range. In general, the rigid body model slightly underestimates the human finger impedance up until 200 Hz. After that, both models give the same results in terms of magnitude. In terms of the phase angle, the rigid body model provides a better fit to the measured human finger impedance. For the model parametrization, the density values of the bones and wobbling masses had to be reduced by half in the rigid body model in order to fit the resonance frequency at about 50 Hz. This results in a finger which weighs less than the human finger. In the flexible body model, the previously stated bone and wobbling mass densities apply. Despite this limitation, the rigid body model offers the greater benefit considering the modeling effort. A purely rigid body approach is also easier transferable to other software packages which might not include the implementation of modally reduced FEM bodies.

The limitations of this contribution are the low number of experimental datasets that were used for the model parametrization. The focus of this contribution, however, was on finding first information about a suitable modeling approach of the human hand. It must be assumed when using a large sample of test subjects and measurement data that the measured impedance values might change. However, we assume that this does not affect the general approach of the dynamic modelling of the human hand.

4. Conclusion and Outlook

This paper addressed the modelling of the human hand in terms of multi body simulations for vibration assessment. Initially it was stated that a potential shortcoming of existing multi body models was the simplified model representation of the hand and the high modeling and computational cost in FE analyses. With respect to the derived research question, it can be concluded that a rigid body modelling approach can provide a sufficient model prediction of the human mechanical impedance. The fingers must be modelled as a bone structure with surrounding wobbling masses which are elastically coupled to the bones.

In future research, the model can now be further developed based on a rigid-body representation. The statistically meaningful analysis of the mechanical impedance of the human hand is the logical next step. Hereby, it will be possible to further parameterize the hand model and finally to couple it with a model of the rest of the arm.

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