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PAPER

# Advancing haptic realism: modelling grasp contact vibrations for enhanced virtual environment interaction

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**Keywords:** haptic technology, grasping interface, high-frequency vibrations, mathematical modelling

## Abstract

In haptic technology, achieving realistic tactile feedback is crucial for enhancing a user's experience in virtual environments. Previous studies lack effective methods for transmitting high-frequency vibrations crucial for realistic tactile feedback in haptic interfaces, highlighting the need for our research to address this gap. This paper explores the application of a tactile gripping interface to transmit the high-frequency vibrations produced when contacting a hard object's surface. These short vibrations improve the tactile sensation of hard virtual surfaces when overlaid on traditional position-based force feedback within a haptic environment. The enhanced realism of virtual objects is achieved by effectively estimating the vibration composition from user-induced parameters. This work presents a prototype grasping interface and empirically demonstrates this device's utility. We examine empirical grasp contact data, recorded and interpreted, to recognise the relationship between dynamic user-controlled parameters and the resulting vibration transients. This relationship effectively incorporates these changing dynamics to model the grasp impact and estimate the essential system parameters to understand the influence of the user's grasp force. Through our multi-point grasping interface design, this work demonstrates a mathematical relationship between the user's grasp force and the high-frequency vibrations from contact with hard surfaces. The study found that the proposed haptic interface achieved an RMSE of 0.05, demonstrating a high level of accuracy. This low RMSE value signifies that the predicted vibrations closely matched the actual measured vibrations, validating the system's capability to generate precise high-frequency transients. Such accuracy is critical for practical applications, including realistic tactile feedback in virtual environments, where precise modelling enhances user experience and interaction reliability. This work provides a foundational model for developing advanced haptic technologies, enabling more immersive virtual environments and precise control in teleoperation and training simulations.

## 1. Introduction

The perception of virtual objects through haptic feedback significantly impacts the quality of the virtual experience. Adequately depicting hard contact with virtual objects is crucial for representing realistic object properties. As demonstrated in the literature [1–3], stimulating the sense of touch with high-frequency acceleration transients can significantly enhance the realism of virtual interactions. High-frequency vibrations are essential in haptic technology as they enable the perception of fine tactile details, such as hardness and texture, by stimulating mechanoreceptors like the Pacinian corpuscles. However, existing studies have primarily focused on low-frequency force feedback, leaving a gap in effectively transmitting high-frequency vibrations.

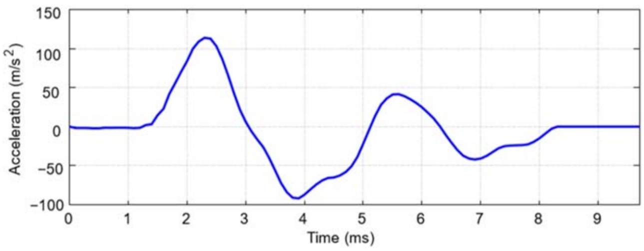


**Figure 1.** Illustrative transient acceleration signal generated during a tapping event, demonstrating the temporal dynamics of vibrations in the time domain.

This research addresses this limitation by integrating high-frequency vibration transmission with traditional force feedback, advancing the realism and applicability of haptic systems in virtual environments.

Understanding the relationship between user-controlled parameters and vibration transients is essential for enhancing the realism of virtual surfaces. Therefore, there is a need to develop effective methods to convey high-frequency vibrations in haptic interfaces. This requires a comprehensive understanding of the system's dynamic behaviour. Investigating methods to achieve this understanding is a critical research issue, addressing a gap in the current literature [4–6].

The ability to experience tactile sensations through touching objects is based on a few fundamental building blocks for humans. The essential components of these primitives for contact perception include normal indentation [7], lateral skin stretch [3], relative tangential motion [8], and vibration [9–11]. While details regarding an unknown material can be obtained via contact with a tool, LaMotte [9] demonstrated that properties such as softness can be discriminated against using a stylus. He showed that discriminating softness by actively tapping with a stylus was substantially better than slow pressing and was unaffected by variations in velocity. Tools commonly form the basis for interaction with the environment by serving as extensions of the hand. Their ability to represent contact information, such as vibration, is especially important as haptic feedback becomes the primary indicator for perception when interacting with hard surfaces in a virtual environment. The focus on this single channel results from the inability to perceive the depth of penetration into the hard surface visually or through proprioception. Actively tapping onto a hard surface with a tool produces high-frequency vibrations. Figure 1 shows the resulting transient acceleration in the time domain, which reflects the temporal dynamics of the impact event. Although high-frequency components are not directly visible in the time domain, this signal forms the foundation for subsequent frequency analysis. The observed transient behaviour is critical for validating the system's capacity to generate vibrations relevant for tactile feedback.

These vibrations stimulate the Pacinian corpuscles, one of the four major mechanoreceptors located deep within the skin's subcutaneous tissue. Pacinian corpuscles are mechanoreceptors strongly associated with the perception of deep-pressure touch and high-frequency vibration [12–15]. They are categorised as fast-adapting (FA) or rapidly adapting (RA), with a frequency bandwidth of 50 to 1000 Hz [16] and a peak response of around 300 Hz [12, 16]. This frequency corresponds to vibrations from active tapping, ranging from tens to thousands of Hz. However, the vibration waveforms produced during contact depend significantly on factors such as the stiffness of the contacted material, the size, shape, and material of the contacting tool, inherent material damping, contact velocity, and finger properties, among others [17, 18]. Modelling contact acceleration transients, such as the one depicted in figure 1, typically involves simplifying the waveform for analytic approximation. The amplitudes of these waveforms vary directly with the impact velocity. At the same time, the frequency and duration are contingent upon both the tool material and the contacted surface [19, 20]. Experiments conducted by LaMotte [9] indicate that perception of stiffness under these conditions primarily relates to the amplitude and frequency of the waveform's attack, leading to contact transients modelled as exponentially decaying sinusoids. Recently, Hirao *et al* [21] demonstrated a tendon vibration enhances pseudo-haptic perceptions in VR by increasing the detection threshold of visual/physical motion discrepancies and amplifying weight perception without compromising resolution, providing new design guidelines for pseudo-haptic applications. Kim *et al* [22] developed a bioinspired, reversible skin-attached haptic interface platform that maintains strong adhesion under both dry and sweaty conditions. It utilizes frog toe pads and snail pedal muscle structures to resist sweat and vibration, enhancing VR applications. Krishnan *et al* [23] identified a machine learning, particularly recurrent neural networks (RNNs), as the most effective method for understanding and predicting tactile sensory processing in autistic people, outperforming behavioural and statistical analyses in accuracy and classification.

The transmission of high-frequency vibrations, essential for realistic tactile feedback in haptic interfaces, has not been adequately addressed in the reported literature. Understanding methods to integrate these high-frequency vibrations with force feedback mechanisms to create more realistic tactile sensations, particularly in the context of gripping interfaces, is crucial. This requires investigating the relationship between user-controlled parameters, such as grasp force, and the resulting vibration transients. This research establishes a mathematical relationship between user grasp force and high-frequency vibrations. By understanding and modeling this relationship, the study contributes to the development of more responsive haptic systems.

The interaction between real objects and hand-held tools generates vibrations above approximately 30 Hz [24]. These vibrations provide rich information humans use to distinguish various object surface properties, shaping our perception and understanding of these objects. In many tasks, humans rely on this information to assess different phases of each task component, such as the precise moment when a push-button on a control panel clicks into place. Representing these valuable high-frequency vibrations through haptic interface technology would enhance the realism of object perception. Achieving this via a haptic grasping interface would significantly enhance a user's ability to interact with virtual objects and extract these desired properties naturally. This research focuses on developing and understanding the contact dynamics through a grasping interface to address this challenge. Identifying the parameters for defining the resulting transients within this interaction is crucial for achieving improved virtual rendering with a multi-point interface using open-loop transients.

A grasping interface [25, 26] works towards a general methodology for displaying vibrations identical to single-degree-of-freedom prototype interfaces within grasp contact interactions. Specifically, this research examines the acceleration transients produced by user-induced forces during grasp contacts with a hard surface. It also investigates a dynamic model based on the first principles of the system-to-impact event to highlight the relationship between user input parameters (such as grasp force), the shape and material of the contacting tool used, and the resulting transient acceleration. As the foundation for realising the innovative design benefits of the grasping interface, this work aims to demonstrate that multi-point devices can represent the necessary vibration signals to enhance the virtual experience. Additionally, it posits that an operator's grasp force can be used to estimate relevant parameters in the user's finger dynamics, affecting the produced vibration transient.

The remainder of this paper is organised as follows: section 2 provides details of the experimental hardware. Section 3 describes the methodology for recording high-frequency transients. Section 4 presents the grasp force and finger dynamics, including system parameter identification, grasp dynamics, and transient scaling. The discussion and conclusions are presented in section 5.

## 2. Experimental hardware

A grasping interface was developed to investigate the effects of user-controllable parameters such as velocity, acceleration, and grasp force on the surface response to an impact with specific materials. The gripper was designed to attach to a standard haptic interface, enabling three degrees of freedom with spatial and grasping with force feedback (figure 2(a)). However, for this study phase, the gripper was immobilised to conduct experiments within a single degree of freedom for grasping.

The experimental system was constructed from aluminium to ensure mechanical bandwidth. In contrast, the original design was based on ABS plastic for lightweight construction. The high-bandwidth system featured a 5 mm diameter steel tip at the grasp contact point. A single finger pad interface point was equipped to gather acceleration, force, and positional (velocity) data while performing grasping tasks on various materials. The system maintained geometric uniformity across both fingers.

Position data were recorded using an E4 miniature encoder from US Digital [27], which provided a resolution of 0.109 mm and was attached to the back of the instrumented gripper pulley. An accelerometer was mounted on the finger pad interface to measure acceleration. This location was chosen to capture transient accelerations directly at the point of grasp contact, ensuring that the recorded signal reflects the dynamic interaction between the user's grasp force and the contacted surface. By minimizing external noise and aligning with experimental objectives, this placement provides accurate and reproducible measurements of high-frequency vibrations critical for this study. Two force sensors were employed—one at the contact point with the sample material and another in contact with the user's finger—as illustrated in figure 2(b). A two-axis accelerometer (Analog Devices ADXL321), with a range of $\pm$ 18 g, was implemented on a custom-printed circuit board featuring a built-in RC low-pass filter set to 1 kHz. The accelerometer's voltage output was sampled at 10 kHz, aligned with the user's fingers (figure 2(b)). Force measurements were obtained using a force sensor (Honeywell FSG15N1A) with 1 kHz bandwidth and a 1.0-gram force resolution.

The system specifications, including hardware components and their functionalities, are summarized in table 1. The system was controlled by a desktop computer running Microsoft Windows XP, with data acquisition handled by a LabJack U3-HV [28] unit. Custom-written control software optimized for the specific task requirements replaced the manufacturer-provided SDK (software development kit).

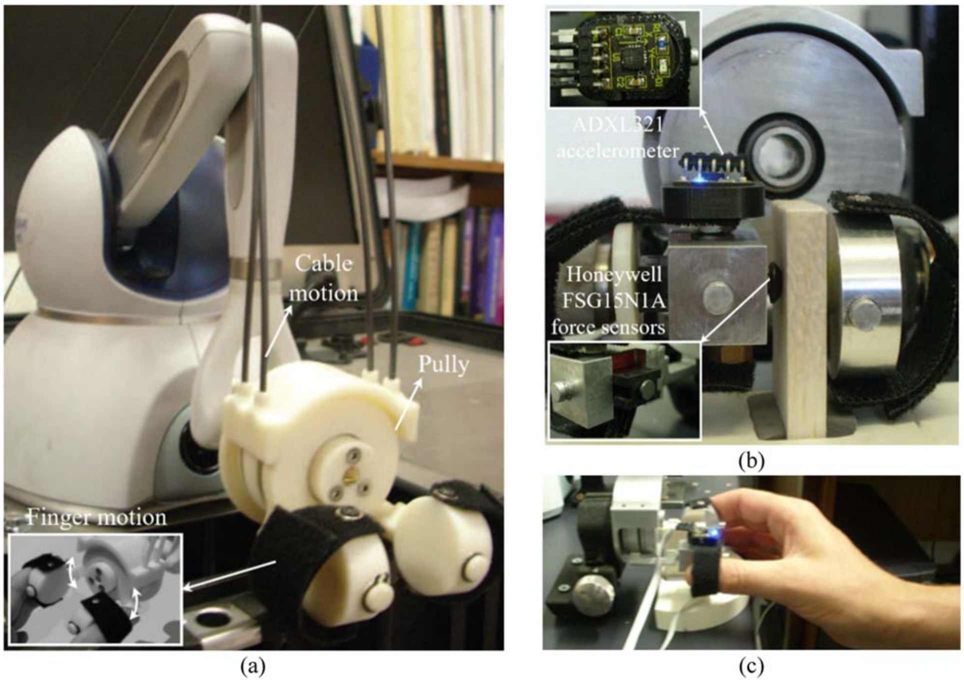


**Figure 2.** Experimental setup: (a) haptic grasping system, (b) ADXL321 accelerometer and Honeywell FSG15N1A force sensors, (c) grasp configuration used in the experiment.

**Table 1.** Specifications of the haptic system and experimental setup.

| Component | Specification | Purpose |
|---|---|---|
| Haptic Interface | Multi-point grasping system with 3 DOF | Captures user inputs for position and force |
| Material Used | Aluminum (mechanical bandwidth), ABS plastic (lightweight) | Ensures system durability and low inertia |
| Accelerometer (ADXL321) | ±18 g range, 10 kHz sampling rate | Measures acceleration transients |
| Force Sensor (FSG15N1A) | 1 kHz bandwidth, 1.0-gram force resolution | Measures grasp force and contact force |
| Data Acquisition System | LabJack U3-HV, 10 kHz sampling rate | Records data for analysis |
| Position Encoder (E4) | 0.109 mm resolution | Captures position data of the gripper |

## 3. Recording high-frequency transients

Experimental tapping data were recorded as grasp impacts were made with the interface held by the index and thumb finger onto a sample of balsa wood affixed vertically to the table, as shown in figure 2(b). Balsa wood was chosen for its material properties, such as frequency response, that align with the bandwidth capabilities of our prototype device mounted on the haptic interface. This setup represents a surface with high-frequency transients but lower stiffness.

The impact event of the gripper contacting the sample provided the necessary parameters of velocity, acceleration, and force through the encoder position, accelerometer, and force sensors, which were recorded before and after the impact. A typical generated signal represents the acceleration transients for contact with balsa wood (figure 3). This signal exhibits minimal noise and falls within the range of the utilised sensors. The noise intensity of the signal increases with the material's stiffness. It is adjusted to eliminate any high-frequency noise and signals beyond the characterised range of the grasping interface.

Data were recorded for a single user to ensure consistent and repeatable experimental conditions, isolating the system dynamics without confounding factors from inter-user variability. This approach aligns with the study's objective of validating the grasping interface's dynamic behaviour under controlled conditions. While this is a foundational step, future studies will expand to larger user cohorts to evaluate inter-user variability and generalize the model further. The user's height was adjusted to ensure their forearm remained level, with the right-hand fingers grasping the interface pads, as illustrated in figure 2(c).

To prevent substantial extension or flexion of the wrist, the subject was instructed to refrain from allowing their hand or arm to touch the table to which the grasping interface was attached. The subject placed their fingers on the interface pads at the central point, concentrating the force along the force sensor's axis. Once in position,

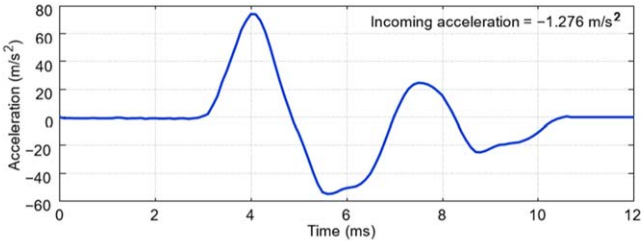


**Figure 3.** Recorded acceleration transient for a tapping event on balsa wood with ($v_{in} = 0.1063$ m s$^{-1}$, $a_{in} = -1.276$ m s$^{-2}$).

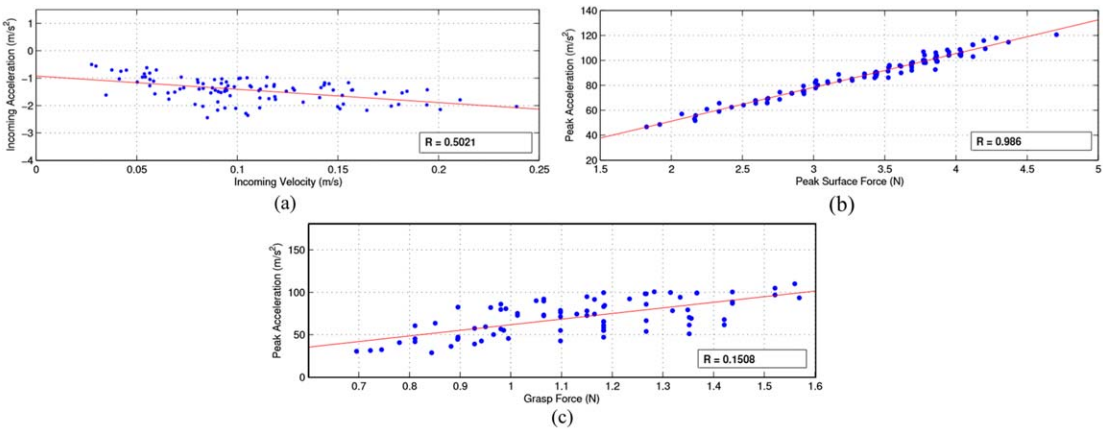


**Figure 4.** The incoming parameters for grasp impacts on the balsa wood sample and the associated correlation coefficient.

their fingers were strapped into place. Securing their fingers to the finger pads enabled the user to manipulate the gripper to complete each grasping impact.

The grasp configuration aimed to be realistic and to enhance the ability to maintain finger force in line with the force sensor for accurate measurements. The subject was coached on grasp configuration and had no trouble maintaining the appropriate posture throughout the experiment, as confirmed by visual inspection. The subject was then instructed to contact the wood sample with the instrumented gripper while varying force levels for each impact event, recording data from the user's thumb. The impact data consisted of 100 grasp contacts, producing the distinct user-controllable parameters shown in figure 4.

To better understand how different transients are produced with grasp impacts on various material surfaces, we utilised the same experimental system shown in figure 2 on a plastic sample. This approach allows for analysing the relationship between the user's input parameters and the resulting output transient. The same user gathered the incoming velocity and acceleration data, along with the peak surface force and grasp force, for 50 grasp contacts. The user was again instructed to use their right hand and the same natural grasp configuration to maintain consistency with previous results.

Dynamic models will be investigated and verified by collecting empirical data and examining the relationships among various parameters. This process will involve identifying the link between these system characteristics and establishing the appropriate dynamic associations.

## 4. Grasp force and finger dynamics

Understanding the relationship between users' changing dynamics and grasp contact vibration is essential for integrating both elements within a haptic simulation. A parametric model of the human finger will be employed to identify these changing dynamics. The incoming grasp force data from the custom interface will be analysed to establish the relationship between this force and the parameters of the impact model.

A second-order underdamped system is selected to model the impact due to its ability to accurately capture the dominant dynamics of the grasping interaction [29–31], including mass, damping, and stiffness. This choice balances simplicity and fidelity, aligning with the scope of the experimental tasks and minimizing overfitting to higher-order effects. Previous studies have validated the suitability of second-order models for similar haptic systems, particularly in representing transient responses in controlled environments. The objective is to identify a low-order model that considers the physical features pertinent to f-force feedback. The model comprises a force, $F$, acting on the finger mass, $m$, linked to the desired finger position, $x_d$, through a damper, $c$, and a spring, $k$ [32]. Although the finger and gripper system may not behave as a linear second-order system across all input ranges, the small forces required for pick-and-place tasks allow a second-order model to examine the essential dynamics for this purpose effectively.

### 4.1. System parameter identification

The impact model for a finger gripper device in contact with a given material can be written by the force balance relationship as:

$$F(t) = m\,\ddot{x}(t) + c\,\dot{x}(t) + k\,x(t) \tag{1}$$

where $m$, $c$, and $k$ are the second-order impact model's parameters, $x(t)$ represents the finger and gripper motion, and $F(t)$ is the input force. Observations of real impacts [10] indicate that acceleration transients typically follow an exponentially decaying sinusoid. Although there is significant uncertainty in the mass parameter $m$ in equation (1), k (the stiffness of the wood) is the dominant component. At the same time, $c$ represents the wood's effective damping and the air's influence between the gripper and the sample material.

The second-order mathematical model enhances the accuracy of simulating haptic feedback by effectively capturing the system's dominant dynamics—mass, damping and stiffness. This approach balances simplicity and precision, ensuring that the transient vibrations closely replicate real-world tactile interactions. By modeling the system as an underdamped mass-spring-damper, the transient response aligns with the physical behavior observed during user contact with hard surfaces. This level of accuracy is critical for generating realistic tactile sensations, particularly in high-frequency vibration regimes where the timing and amplitude of transients directly influence the user's perception of hardness and texture. The use of this model reduces computational overhead compared to higher-order models while maintaining fidelity, making it suitable for real-time applications such as virtual training and teleoperation. Future work may extend this approach to include nonlinearities and multi-material scenarios to further improve its applicability.

Taking the Laplace transform of equation (1), the system transfer function can be formulated as follows:

$$\frac{X(s)}{F(s)} = \frac{G\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{2}$$

in which $\zeta$ is the damping ratio, $\omega_n$is the natural frequency, and $G$ is the system's gain. The transient output of a step response is:

$$x(t) = G\left(1 - \frac{1}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t} sin(\omega_n\sqrt{1-\zeta^2}\,t + \varphi)\right) \tag{3}$$

where $\varphi = \cos^{-1}\zeta$.

The model parameters are estimated using least-squares approximation, where acceleration transients are measured for each grasp contact experiment. The expected small displacements within the range of $10^{-6}$ $x(t)$ were estimated through integration and double integration, respectively. A Honeywell force sensor was located under the user's finger and at the contact point with the sample material to measure incoming force and peak surface force. Through least-squares approximation for each experiment, we can obtain a set of parameters deemed acceptable only if they are consistent between experiments.

The variance of parameter estimation can be quantified using statistical measures such as Root Mean Square Error (RMSE). With higher-performance recursive parameter estimation methods, such as those available through MATLAB, we can validate the performance of the estimated parameters. The optimisation procedure minimises the RMSE and is a multivariable nonlinear function.

For validation, the transfer function must take the following form:

$$\frac{X(s)}{F(s)} = \frac{K}{T_\omega^2 s^2 + 2\zeta T_\omega s + 1} \tag{4}$$

where $K$ is the newly calculated gain of the model. Based on the presented empirical results, a very small value of $K$ is expected due to the minimal displacement caused by the impact vibration. Substituting $K$ and $T_\omega$ into equation (3) gives:

$$x(t) = K\left(1 - \frac{1}{\sqrt{1-\zeta^2}}e^{\frac{-\zeta}{T_\omega}t}\sin\left(\frac{\sqrt{1-\zeta^2}}{T_\omega}t + \varphi\right)\right) \tag{5}$$

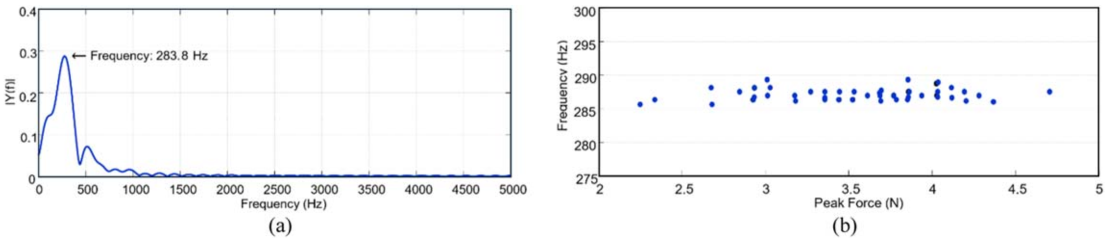


**Figure 5.** Acceleration transient frequency: (a) frequency spectrum of a typical transient (single-sided amplitude spectrum of y(t)), (b) frequency and peak surface force.

While equation (4) represents the system with a force input-to-position output relationship, the empirical data of the transients is represented by acceleration. Therefore, it must be described by the second derivative of equation (4) to produce the transfer function relating the desired acceleration output to the grasp force input as follows:

$$\frac{a(s)}{F(s)} = \frac{Ks^2}{T_\omega^2 s^2 + 2\zeta T_\omega s + 1} \tag{6}$$

and step response:

$$\frac{d^2x(t)}{dt} = -K\left(\frac{1}{T_\omega^2\sqrt{1-\zeta^2}}e^{\frac{-\zeta}{T_\omega}t}\sin\left(\frac{\sqrt{1-\zeta^2}}{T_\omega}t + \varphi\right)\right) \tag{7}$$

For the system with a unit step input described by equation (6), the settling time $T_s$ is defined as the duration the system stabilises within a specified input amplitude percentage. Since the transient output represents the system's response to a grasping impact and each transient is short in duration, we estimate the system parameters for a sample acceleration by fitting an exponential envelope to the peak acceleration at 15%. This shows that the settling time occurs approximately when $e^{-\zeta\omega_n T_s} < 0.15$ leads to $T_s = 2\tau$.

The settling time of the vibration output for the generated samples demonstrated consistency for $\pm$ 15% within the measured peak acceleration transient output.

In this underdamped case, the damped frequency $\omega_d = 2\pi F_d$ and natural frequency $\omega_n = \frac{2\pi F_d}{\sqrt{1-\zeta^2}}$ where $F_d$ is the frequency of the acceleration transient. This frequency is determined through the Fourier transform of the transient, where a rough estimate can be extracted from one oscillation period. A typical case is shown in figure 5(a), which also indicates other frequency components found in the vibration. Throughout the experiments described in the previous section, the trial system was not altered in any way, thereby assisting in determining whether the frequency of each output acceleration transient was constant for the same material. Figure 5(b) represents the consistency of this frequency across the measured sample range and demonstrates the essential linearity of the experimental hardware. This approximately linear trend suggests conformity of the experimental system in contact with the sample material through the significance of frequency in equation (6).

With these primary parameters known, $T_\omega$, $\zeta$, and $K$ are determined by:

$$T_\omega = \frac{T_s\zeta}{2} \tag{8}$$

and

$$T_\omega = \frac{\sqrt{1-\zeta^2}}{2\pi F_d} \tag{9}$$

where $\zeta$ is calculated through:

$$\zeta = \frac{1}{\sqrt{\left(\frac{2\pi F_d}{2}T_s\right)^2 + 1}} \tag{10}$$

The new gain of the model is now calculated using the parameters $T_w$, $\zeta$ and $a_{peak}$, as found through equation (7):

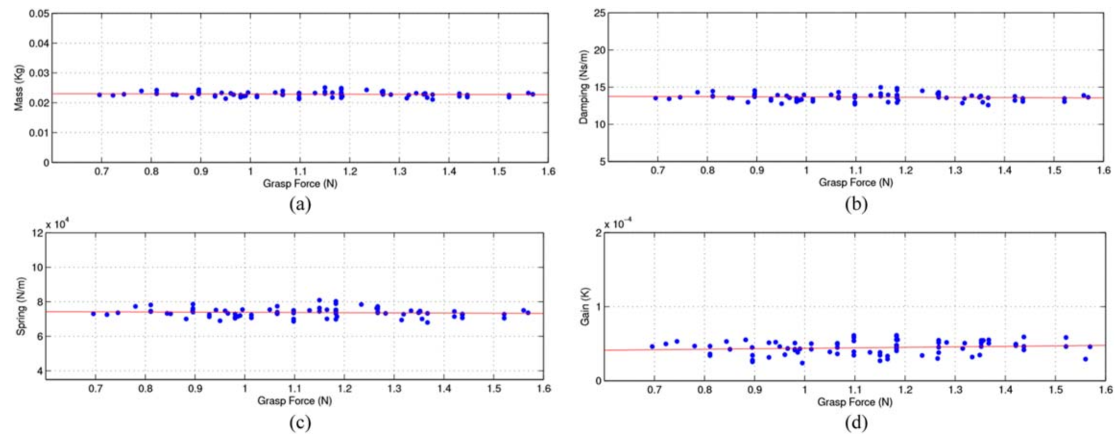

**Figure 6.** Empirical relationship between grasp force and (a) mass, (b) damping, (c) stiffness, (d) gain.

$$K = \frac{a_{peak}}{e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}}} T_\omega^2 \sqrt{1 - \zeta^2} \quad (11)$$

where $a_{peak}$is the peak acceleration after the grasp impact.

With equation (6) linking the input force (grasp force) to the acceleration output, the peak acceleration calculates the new gain in equation (11), forming a new scaling component between grasp force and acceleration.

Using the least squares technique, the parameters $m$, $c$, and $k$ can be estimated from the data shown in figure 6. The parameter estimates demonstrate a clear correlation between grasp force and the dynamics of the finger/gripper combination during grasp impacts on real surfaces.

The resulting parameters obtained from linear fits are as follows: $m = 0.023$ kg–0.00032 kg/N $\cdot F_{grasp}$, $c = 14$ Ns/m–0.19 s/m $\cdot F_{grasp}$, $k = 75000$ N m$^{-1}$–10001/m $\cdot F_{grasp}$.

Observation of the results suggests similar findings from other haptic researchers, including tapping results observed by Howe [33] and Fiene and Kuchenbecker [34]. As seen in figure 6, the estimated parameters show a decreasing trend, which can be attributed to the small range in grasp force. While the mass should remain constant for each grasp impact and across all ranges of grasp forces, it decreases slightly with increasing force. Extensive investigation of the mechanical impedance of the finger in a pinch grasp suggests that changes in finger posture with increasing force resulted in variations in the estimated inertia for finger extension [35]. Changes in posture were not observed throughout the experiment; however, the established radial motion and grasp distance of the interface could contribute to this. The tapping results of wood on a foam substrate by Fiene and Kuchenbecker [34] suggest similarity in damping and stiffness, considering our experiment utilised a firmly fixed wood sample.

### 4.2. Grasp dynamics and transient scaling

As demonstrated, the evident relationship between user-controlled parameters and high-frequency acceleration transients in our grasping interface has led to the investigation of the second-order model shown in equation (6) and the step response in equation (7). Representing these transients by overlaying them on top of traditional position-based force feedback has been addressed by various researchers. Previous work has involved scaling or indexing the contact transient amplitude by the user's impact velocity [17, 32, 34]. While this approach can provide an improved representation of virtual objects, it limits the exploration of user-changing dynamics, such as grasp force, to understand this relationship more substantially.

The system used by Fiene and Kuchenbecker [34] is based on vertical tapping tasks with a one-degree-of-freedom haptic interface. The grasped stylus incorporates a force sensor to measure grip force during taps and an ATI force sensor placed under the sample material to measure peak surface force. Their study demonstrates a roughly linear relationship between incoming velocity and the peak transient force through momentum analysis of the haptic system. He also shows that both incoming acceleration and grip force influence the amplitude of the acceleration transient. Fiene's approach to highlighting the effect of grip force on vertical tapping tasks has motivated a system identification and modelling approach to characterise our multi-point grasping interface for high-frequency grasping transients.

While Fiene showed that grip force and other incoming parameters influence the amplitude of the transient, our grasping interface allows grasp force to impact the system mass directly, providing an added user-controlled parameter. Placing force sensors at the user's finger enables measurement of varying grasp force through the

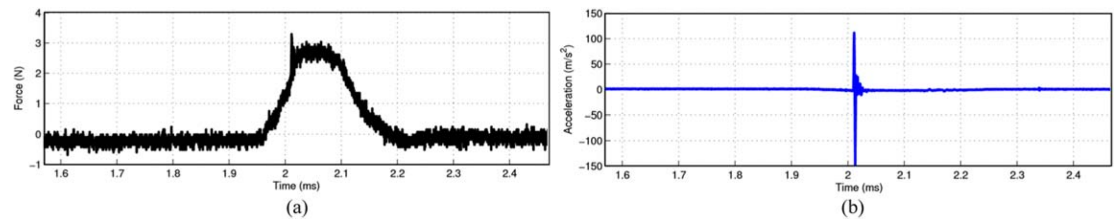


**Figure 7.** (a) Typical grasp force profile, (b) acceleration transient for contact with balsa wood.

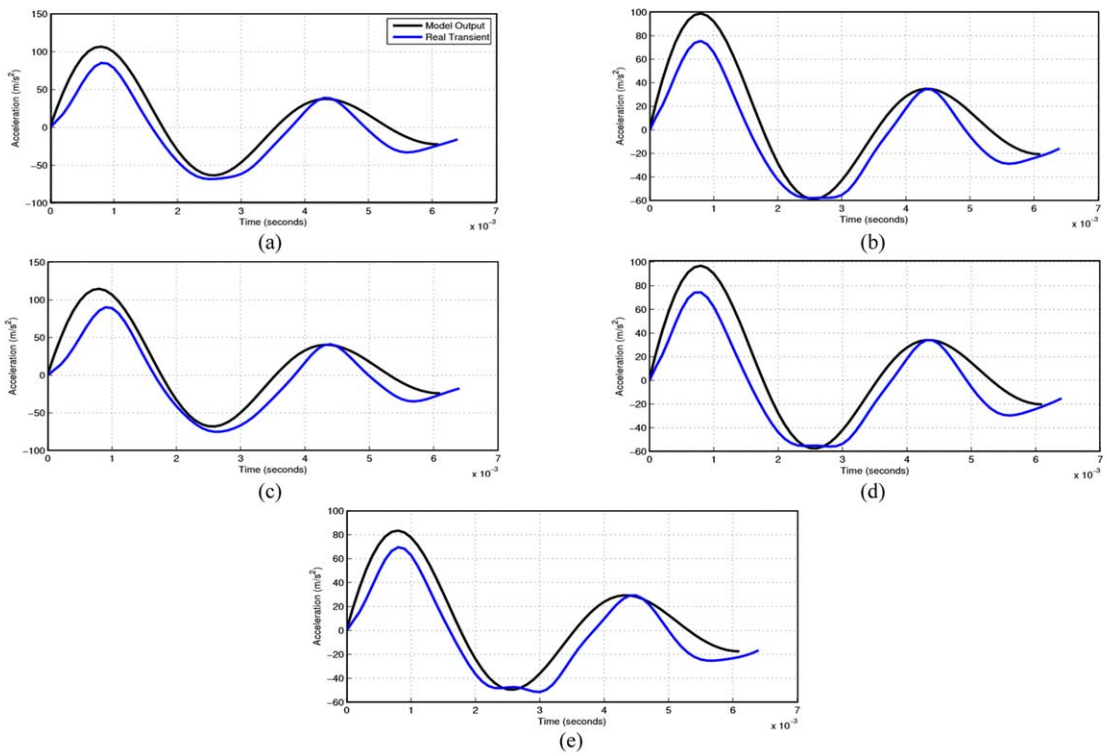


**Figure 8.** Comparison of the generated acceleration transient from the impact model with the original transient data.

radial motion of the grasping interface. This section investigates how changing grasp dynamics of the hand, and fingers can contribute to scaling the vibration transients through the user's grasp force.

Exhibiting the approximate linear relationship between the user's grasp force and the peak amplitude of the acceleration transient shown previously, the profile of the user's grasp force and the resulting transient is depicted in figure 7.

Using the least-squares parameter estimates from the previous section and observing the characterised trend of user input parameters on the amplitude of the acceleration transient, this correlation is employed to scale the transient response of the linear system. This approach produces a simulated representation of the corresponding real acceleration transient.

Samples of real user-applied grasping forces were used to numerically validate the second-order model against the corresponding acceleration transient data to identify the system response to varying grasp forces. The measured grasping impact dynamics parameters of $m = 0.023$ kg, $c = 14$ Ns/m and $k = 75000$ N m$^{-1}$ were simulated for several grasp force input values. This simulation compared the real acceleration and the simulated result, as shown in figure 8.

As depicted in the figures, the simulated transients closely represent the original acceleration impact data. While the peak acceleration deviates slightly due to the smoothing of the transient, filtering was applied to eliminate high-frequency electrical noise and signals beyond the characterised range of the grasping interface.

Validation of the estimated parameters was conducted by comparing the response output generated by our parameters with the output generated using recursive parameter estimation techniques in MATLAB. This approach employs recursive techniques for parameter estimation that directly calculate optimal parameter estimates at each time step, providing a performance indication of how our estimated parameters compare with an online estimation approach. The results are quantified through the RMSE between the estimated and actual transient responses.

Equation (6) must be modified to include a process zero numerator term to use the correct form of the transfer function in MATLAB. This adjustment is necessary to maintain the force input to acceleration output relationship, as the original transfer function applied in MATLAB operates on a force and position dependency.

Reconstructing equation (6) to include a process zero results in:

$$\frac{a(s)}{F(s)} = \frac{K}{T_\omega^2} - \frac{\frac{K}{T_\omega^2}(2\zeta T_\omega s + 1)}{T_\omega^2 s^2 + 2\zeta T_\omega s + 1} \tag{12}$$

where the process zero $T_z = 2\zeta T_\omega$ and $K_{new} = \frac{K}{T_\omega^2}$ form the new gain of the system. Manipulating equation (12) allows for the use of the previously estimated parameters $T_\omega$, $\zeta$, and $K$, which can be applied in the following form:

$$a(t) = \frac{K}{T_\omega^2} f(t) - L^{-1}\left(\frac{\frac{K}{T_\omega^2}(2\zeta T_\omega s + 1)}{T_\omega^2 s^2 + 2\zeta T_\omega s + 1}\right) \tag{13}$$

The inverse Laplace term forms the transfer function suitable for MATLAB use. It adheres to the rules of a proper model, ensuring that the degree of the numerator is less than that of the denominator. The previously estimated parameters are applied to the time-domain components of equation (13). Due to the performance of the recursive parameter optimisation approach, a double-nested recursive estimator was used to determine the new acceleration by:

$$a_{new}(n) = a(t) - \frac{K(n-1)}{T_\omega^2(n-1)} \tag{14}$$

This new acceleration is then applied, along with the corresponding force of the original transient, to the recursive estimation technique to estimate the new parameters $T_\omega(n)$, $\zeta(n)$, and $K(n)$.

A comparison between the original transient and the recursive output can be obtained by applying the same grasp force input values used in figure 8 and the new acceleration from equation (14). To understand how the manually estimated parameters compare to the recursive estimates, they were plotted against each other to illustrate the differences between the two estimation techniques, as illustrated in figure 9.

The performance is evaluated based on manually and recursively estimated parameters. This assessment quantifies the discrepancy between the simulated output transients and the original acceleration transient, as depicted in table 2.

Looking at the results presented in figure 9, it is clear that the scaling of the grasping force directly influences the resultant acceleration transient, as observed in the empirical data shown earlier. Table 2 listed the effectiveness of the parameter estimation technique compared to the recursive parameter estimation approach.

### 4.3. Methodological limitations and implications

While this study provides valuable insights into the modelling and transmission of high-frequency vibrations in haptic systems, it is important to acknowledge its methodological limitations. First, the experiments were conducted with a single participant to maintain controlled and consistent conditions. Although this approach allowed for precise evaluation of the system dynamics, it limits the ability to generalize the findings across a diverse user population. Variability in factors such as hand size, grip strength, and interaction preferences may influence the applicability of the model in broader contexts.

Second, the evaluation was restricted to two materials (wood and plastic). While these materials were chosen to represent distinct stiffness and damping properties, they do not encompass the full range of textures and material characteristics encountered in real-world applications. The absence of testing on softer or more complex materials may limit the generalizability of the model to such scenarios.

Future studies should address these limitations by incorporating larger and more diverse participant groups to capture inter-user variability and extending the evaluation to a broader array of materials. These steps will ensure a more comprehensive validation of the model and enhance its applicability across diverse use cases.

### 4.4. Practical implications for haptic device design and VR applications

The findings of this study have significant practical implications for the design and application of haptic devices, particularly in the virtual reality (VR) industry. The validated second-order mathematical model provides a

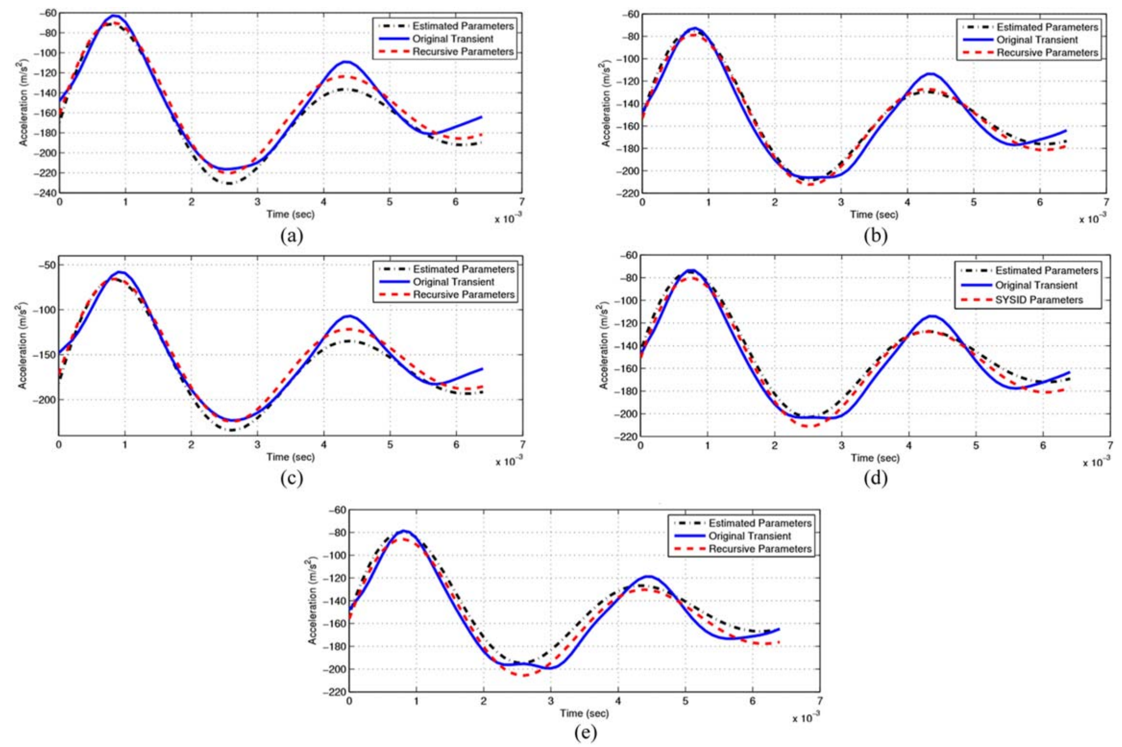


**Figure 9.** Comparison of the generated acceleration transient using equation (13): recursive parameters versus manually estimated parameters against the original transient.

**Table 2.** Performance comparison of manually estimated parameters and recursively estimated parameters.

| Transient | Optimised $\text{Fit}_{\text{manual}}$ | Optimised $\text{Fit}_{\text{recursive}}$ |
|---|---|---|
| 1 | 71.54 | 80.94 |
| 2 | 79.59 | 81.36 |
| 3 | 72.31 | 80.37 |
| 4 | 74.74 | 80.34 |
| 5 | 69.82 | 80.35 |

framework for integrating high-frequency vibrations into haptic systems, allowing for more realistic tactile feedback. This advancement enhances user interaction by enabling precise perception of material properties such as hardness and texture in VR environments.

The demonstrated accuracy of the model (RMSE = 0.05) supports its application in scenarios where precise tactile feedback is essential, such as surgical training, remote manipulation, and gaming. For example, incorporating this model into multi-point haptic interfaces can improve the fidelity of virtual object manipulation, creating immersive experiences that closely mimic real-world interactions. Additionally, the scalability and computational efficiency of the model make it feasible for real-time applications, addressing a critical requirement for VR-based training simulations and teleoperation systems.

Future work could explore how this model adapts to diverse materials and complex interaction dynamics, further expanding its usability in advanced VR and haptic applications.

## 5. Conclusions

The integration of high-frequency vibrations with force feedback mechanisms to create more realistic tactile sensations in haptic interfaces addresses a significant gap in the field. A novel haptic grasping interface was introduced to investigate its capability to generate high-frequency vibrations upon contact with hard surfaces. The assessment of results revealed effective modelling of grasp impact dynamics between the gripper and firm surfaces. Initially, empirical grasp contact data were recorded and analysed to establish a correlation between dynamic user-controlled parameters and resulting vibration transients. With direct access to the user's grasp force, the study demonstrated a linear relationship between grasp force and the amplitude of output transients. A second-order mass-spring-damper model was employed to model the system dynamics during gripper contact with sample materials. System parameters were estimated and found to correlate linearly with user grasp force. The system's linearity was confirmed through consistent frequency responses across different material samples and the consistency of parameters m, c, and k. While a user's grasp dynamics are complex and not easily captured by a simple model, the results affirm the effectiveness of utilizing user grasp force to generate appropriate acceleration transient responses. This study empirically demonstrated the utility of the proposed haptic interface and validated its accuracy with an RMSE of 0.05. This objective validation proves the effectiveness of the methods used and highlights the potential for practical applications. In summary, this study has highlighted the system's linearity, establishing a clear relationship between user grasp force and its ability to generate acceleration transients that accurately represent empirically generated responses within virtual environments.

Future research could focus on expanding participant diversity to capture user variability, evaluating a broader range of materials to enhance generalizability, and incorporating nonlinear dynamics for improved real-world accuracy. Additionally, integrating the model into real-time haptic systems and exploring multi-sensory feedback could advance applications in VR, teleoperation, and gaming.

## Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

## Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

[1] Avila R S and Sobierajski L M 1996 A haptic interaction method for volume visualization '96 *Proc. Seventh Annu. IEEE Vis. (San Francisco, CA, USA, 1996)* pp 197–204
[2] Adams R J and Hannaford B 1999 Stable haptic interaction with virtual environments *IEEE Trans. Robot. Autom.* **15** 465–74
[3] Kuchenbecker K J, Park J G and Niemeyer G N 2003 Characterizing the human wrist for improved haptic interaction *Proceedings of the ASME 2003 International Mechanical Engineering Congress and Exposition. Dynamic Systems and Control* 1 *(Washington, DC, USA, 2003)* pp 591–8
[4] Lin W *et al* 2023 Programmable and ultrasensitive haptic interfaces enabling closed-loop human–machine interactions *Adv. Funct. Mater.* **33** 2305919
[5] Qi B, Zhang M, Zhu X, Jiang Y and Xiang X 2024 Effects of haptic interaction on learning performance and satisfaction with 3D collections *Educ. Inf. Technol.* **29** 7793–811
[6] Hwang G W *et al* 2024 A spatially selective electroactive-actuating adhesive electronics for multi-object manipulation and adaptive haptic interaction *Adv. Funct. Mater.* **34** 2308747
[7] Dhong C, Miller R, Root N B, Gupta S, Kayser L V, Carpenter C W, Loh K J, Ramachandran V S and Lipom D J 2019 Role of indentation depth and contact area on human perception of softness for haptic interfaces *Sci. Adv.* **5** eaaw8845
[8] Willemet L, Kanzari K, Monnoyer J and Wiertlewsk M 2021 Initial contact shapes the perception of friction *Proc. Natl Acad. Sci.* **118** e2109109118
[9] LaMotte R H 2000 Softness discrimination with a tool *J. Neurophysiol.* **83** 1777–86
[10] Wang X, Xu B, Zhang W, Wang J, Deng L, Ping J, Hu C and Li H 2023 Recognizing emotions induced by wearable haptic vibration using noninvasive electroencephalogram *Front. Neurosci.* **17** 1219553
[11] Gong Y, Husin H M, Erol E, Ortenzi V and Kuchenbecker K J 2024 AiroTouch: enhancing telerobotic assembly through naturalistic haptic feedback of tool vibrations *Front. Robot. AI* **11** 1355205
[12] Westling G and Johansson R S 1987 Responses in glabrous skin mechanoreceptors during precision grip in humans *Exp. Brain Res.* **66** 128–40
[13] Bajwa H and Al Khalili Y 2019 Physiology, Vibratory Sense. 2023 May 1. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2025 Jan–. PMID: 31194428
[14] Plater E B 2022 *Effects of Stochastic Resonance on Perception and Cutaneous Reflexes in the Lower Limb* (Univ. Guelph)
[15] Richards C 2023 *Wearable Sound: Integrative Design for Hearing and Feeling Vibrations* (Sorbonne Univ)

[16] Kwon J, Park S W, Sakamoto M and Mito K 2021 The effects of vibratory frequency and temporal interval on tactile apparent motion *IEEE Trans. Haptics* **14** 675–9

[17] Wee C, Yap K M and Lim W N 2021 Haptic interfaces for virtual reality: challenges and research directions *IEEE Access* **9** 112145–62

[18] Pediredla V K, Chandrasekaran K, Annamraju S and Thondiyath A 2022 Design and realization of a novel haptic graspable interface for augmenting touch sensations *Front. Robot. AI* **9** 927660

[19] Walker J M, Culbertson H, Raitor M and Okamura A M 2017 Haptic orientation guidance using two parallel double-gimbal control moment gyroscopes *IEEE Trans. Haptics* **11** 267–78

[20] Gleeson B T and Provancher W R 2010 Exploration of tactile contact in a haptic display: effects of contact velocity and transient vibrations *IEEE Trans. Haptics* **4** 88–99

[21] Hirao Y, Amemiya T, Narumi T, Argelaguet F and Lécuyer A 2024 Leveraging tendon vibration to enhance pseudo-haptic perceptions in VR *IEEE Trans. Vis. Comput. Graph.* **30** 5861–74

[22] Kim J, Hwang G W, Song M, Lim D, Kim J-L, Choi J-H, Lee Y S, Kim D W, Yang T-H and Pang C 2024 A reversible, versatile skin-attached haptic interface platform with bioinspired interconnection architectures capable of resisting sweat and vibration *Adv. Funct. Mater.* **34** 2311167

[23] Krishnan K, Jomhari N, Ayyasamy R K, Abdul Kareem S and Krishnan S 2024 Haptic feedback: an experimental evaluation of vibrations as tactile sense in autistic people *IEEE Access* **12** 81088–104

[24] Barbagli F, Salisbury K and Devengenzo R 2004 Toward virtual manipulation: from one point of contact to four *Sens. Rev.* **24** 51–9

[25] Najdovski Z and Nahavandi S 2008 Extending haptic device capability for 3D virtual grasping *Haptics: Perception, Devices and Scenarios: 6th Int. Conf. EuroHaptics 2008 Madrid, Spain, 2008 Proc* 6, 494–503

[26] Najdovski Z, Nahavandi S and Fukuda T 2012 Design, development, and evaluation of a pinch–grasp haptic interface *IEEE ASME Trans. Mechatron.* **19** 45–54

[27] US Digital Pty Ltd https://usdigital.com/

[28] Labjack Corporation https://labjack.com/

[29] Becker J and Mote C Jr 1990 Identification of a frequency response model of joint rotation *J. Biomech. Eng.* **112** 1–8

[30] Van der Kooij H, Fricke S S, van't Veld R C, Prieto A V, Keemink A Q L and Schouten A C 2022 Identification of hip and knee joint impedance during the swing phase of walking *IEEE Trans. Neural Syst. Rehabil. Eng.* **30** 1203–12

[31] Grimmer M, Zeiss J, Weigand F, Zhao G, Lamm S, Steil M and Heller A 2020 Lower limb joint biomechanics-based identification of gait transitions in between level walking and stair ambulation *PLoS One* **15** e0239148

[32] Roy D 2021 Vibration of compliant robotic grippers and wrists *Modeling and Computation in Vibration Problems, Vol. 1: Numerical and Semi-analytical Methods* (IOP Publishing Bristol) 11-1–11-74

[33] Howe R D 1993 Tactile sensing and control of robotic manipulation *Adv. Robot.* **8** 245–61

[34] Fiene J P and Kuchenbecker K J 2007 Shaping event-based haptic transients via an improved understanding of real contact dynamics *Second Joint EuroHaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst. (WHC'07)* pp 170–5

[35] Chen H, Langlois K, Brancart J, Roels E, Verstraten T and Vanderborght B 2023 A novel physical human robot interface with pressure distribution measurement based on electrical impedance tomography *IEEE Sens. J.* **23** 21914–23