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Vibroacoustic Investigations on Hand Prostheses and Sound Design

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ABSTRACT

Modern hand prostheses are capable of mimicking finger or wrist movements using electrical motors, gear mechanisms and control elements. The drive systems and the transmission mechanisms emit machinery noises which can activate or enforce a foreign body sensation by users. Transfer-path-analysis is originally developed to investigate the individual vehicle noise paths. It is a useful tool for troubleshooting and optimization of the product sound quality. In this study, the vibroacoustical characteristics of a hand prosthesis are investigated using the transfer-path-analysis. First of all, the acoustical behaviour of the electrical motor is investigated. The electrical motor is coupled with supporting structures to cause mechanical vibrations of the housing, which, in some instances, radiates acoustical energy. Therefore sound and vibration measurements are carried out to determine the airborne and the structureborne transfer characteristics of the structural elements of the hand prosthesis. According to Jekosch the perceived quality of an entity results from the judgment of the perceived characteristics of an entity in comparison to its desired/expected characteristics [1]. Thus, an interview with prosthesis users is conducted to characterize the user expectations regarding prostheses sounds. A psychoacoustical experiment is carried out to evaluate the sounds regarding their reliability and pleasantness. The results of this study convey useful constructive design ideas for hand prostheses concerning the sound quality.

MYOELECTRIC PROSTHESES AND THEIR SOUNDS

The development of new sensor and actuator technologies in recent years is reflected in the progress of prostheses industry. Myoelectric prostheses can measure and interpret the residual muscular activities (action potentials) with the help of their sensors. Using this information, they generate control signals for electromechanical elements and conduct different movements, such as opening and closing of the hand, adaptive grasp, wrist rotation, elbow flexion, etc. Usual prosthetic hands are basically pinch type devices with two rigid fingers and a rigid thumb. These prostheses can achieve a two or three point contact with objects that are grasped. During grasping, the operation of electromechanical elements causes a noise. Such kind of noises can be troublesome or unpleasant for users, because of different reasons such as their machinelike character which reminds of robot movements, frequency spectrum or modulation features, etc. The expectations of the prosthesis users play an important role on the quality evaluation.

The aims of this study are the investigation of the vibroacoustical behaviour of a myoelectric hand prosthesis and the rules behind of its sound quality. In order to achieve these aims, a work plan was followed which includes different steps: the characterization of the user expectations regarding prostheses sounds, the investigation of the vibroacoustical behaviour of the hand prosthesis using transfer path analysis and the evaluation of the existent and designed prostheses sounds.

USER EXPECTATIONS REGARDING PROSTHESIS SOUNDS

The purpose of this part of the study was to prepare a catalog of user requirements regarding the features of the prosthesis sounds. Therefore an interview with prostheses users was conducted. Eighteen representative users, eleven men and seven women, aged between 12 and 80 years old, participated in this interview. They were paid on an hourly basis. The following criteria were evaluated in this interview:

- The annoyance of the sound of prosthesis, which is daily used.
- Description of the sound of existing prostheses.
- Which feedback modality (visual, auditory, tactile) is normally used to control the operation of the prosthesis?
- Does sound play any role as feedback during the prosthesis usage?
- How should a prosthesis sound? Which noise behaviour is required (no sound, unobtrusive sound, no matter)?

- Does sound deliver any information on the quality of prosthesis?

The annoyance regarding the sounds of daily used prostheses was evaluated on a quasi-continous scale (1: not at all, 10: extremely). The results are shown in Figure 1.

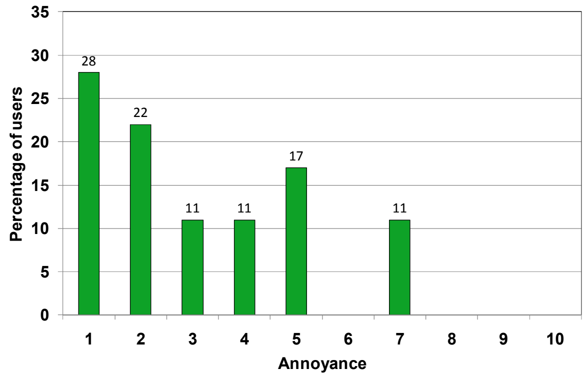

Figure 1. The annoyance judgments of the prosthesis users regarding the sound of their own prosthesis.

The interpretation of the results allows us to define two user groups: 1) Level of annoyance 1-3: Users perceive sounds as not annoying, 2) Level of annoyance 4-7: Users perceiving sounds as annoying. Those probands, who describe the noise of their own prosthesis as rattling and/or rubbing, complain about the noise annoyance, whereas probands, who describe the noise as buzzing, does not have any complaint about the annoyance.

A conventional hand prosthesis can reproduce natural hand motions but cannot deliver any tactile feedback to the user. Figure 2 shows how often sound is used as feedback for different purposes such as successful operation, velocity, force-regulation, etc.

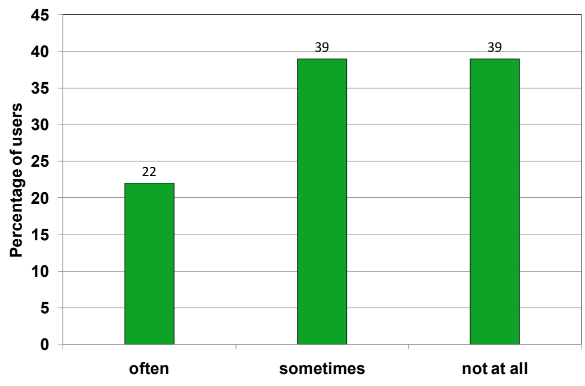

Figure 2. Frequency of usage of the sound as feedback.

Figure 3 shows which feedback modality is normally employed to control the operation of the prosthesis. Auditory modality is used by more than half of participants. Hovewer the visual modality is the most important one. Two reasons for the few usage of the tactile modality are possible: the prosthesis does not generate any active tactile feedback, as well as, the participants have lost their tactile abilities in different levels. Therefore tactile feedback should be individually designed, if required.

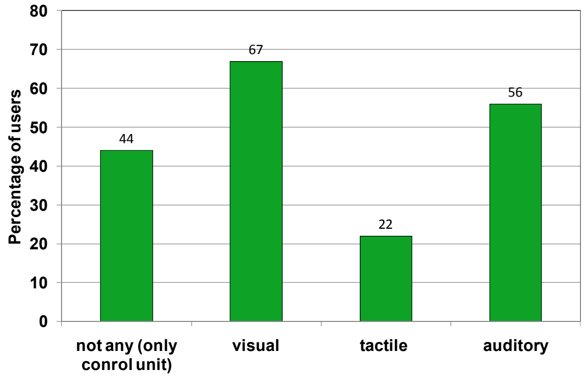

Figure 3. The feedback modality which is normally used to control the operation of the prostheses (multiple entries possible).

Figure 4 shows the desired sound character for the prosthesis. Most of the participants would like to have an unobtrusive sound. At the beginning of study the prosthesis developers thought that their products should not be audible. So, this result is very interesting,

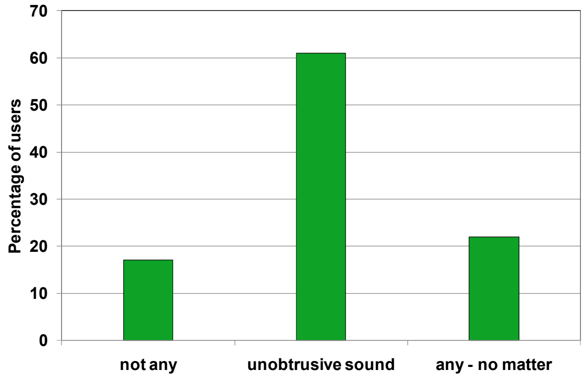

Figure 4. Desired sound character for prosthesis sound.

Approximately half of the participants expect that the sound of a prosthesis delivers important cues on the quality of the product (Figure 5).

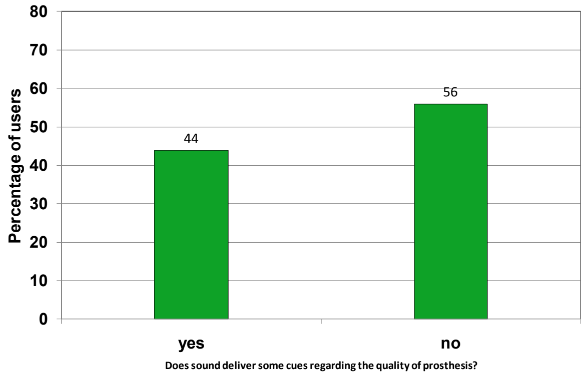

Figure 5. The judgments on if sound delivers any information on the quality of prosthesis.

VIBROACOUSTICAL INVESTIGATIONS

The transfer path analysis was originally developed in order to predict the interior noise of vehicles [2]. The airborne and structureborne sound transmission are two main paths of the noise generation. Based on different noise sources, various airborne and structureborne transfer functions should be experimentally or numerically (simulation) determined. In this study, a transfer path analysis was conducted to understand the noise generation mechanisms and to identify important paths of a hand prosthesis.

The handprosthesis, which was investigated in this study, is a SensorHand SPEED by the company Otto Bock. It is a myoelectric hand prosthesis. The fundamental operation principles of the myoelectric hand prostheses were described above. The main noise sources are the electrical motor and transmission mechanisms (Fig. 6) (see for detailed information on electrical motor noise and vibration [3]).

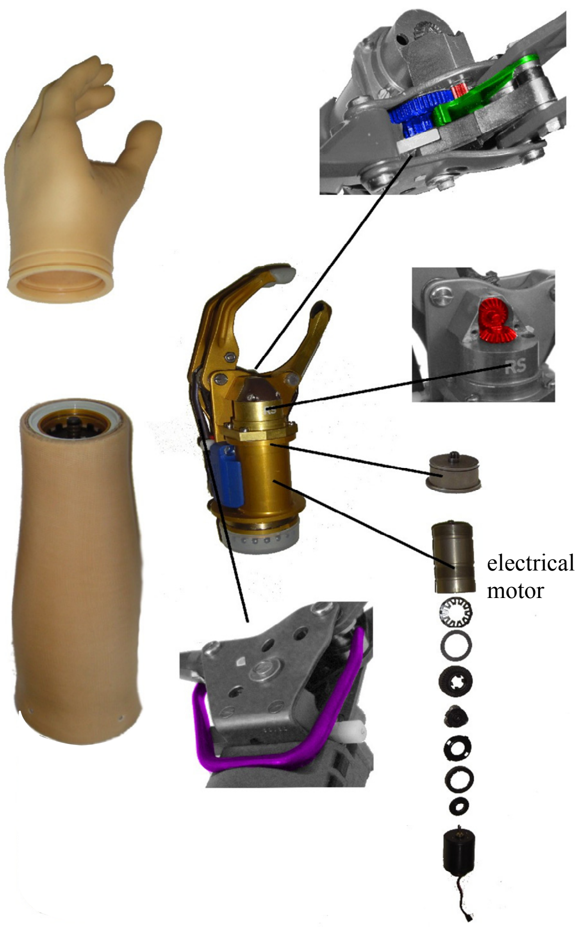

Figure 6. SensorHand SPEED by Otto Bock [4].

First of all, the acoustical behaviour of the electrical motor is investigated. The excitation spectrum of the motor consists of the fundamental frequency of the rotating speed at “250 Hz” and its harmonics at “500 Hz, 750 Hz and 1000 Hz”. Impulse response of the motor housing shows that there are some eigen frequencies at 2.3, 4.7 kHz to 5.2 kHz and 13 kHz. The noises of the brushes and bearing or of the aerodynamical parts cause various tonal components at the frequency range from 8 kHz to 16 kHz. The tonal components of the transmission elements are shown in Figure 7.

The vibroacoustical transmission paths of the prosthesis are shown in Figure 8. In order to determine the transmission functions qualitatively, the system should be excited by standard drive system. It is possible to generate a sweep excitation (increasing rotation speed) by controlling the voltage.

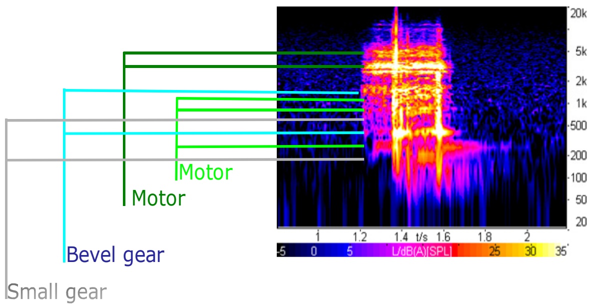

Figure 7. Spectrogram of the sound which was generated during hand closing (frequency components of different sources).

The investigations show that the silicon glove has a low-pass character (Cut-off frequency: 1000 Hz, 20 dB per decade). Thus, most of the high frequency components of the noise are removed by the silicon glove. At the same time there is no influence on low frequencies. The significant amount of low frequency components are radiated by shaft. The structure-borne noise of the motor and hand mechanics is transmitted to the structure of prosthesis shaft and excites it to vibrate. Because of its geometry (funnel-shaped), the shaft exhibits many fundamental frequencies at low frequency range. Therefore the low frequency noise components are amplified. For high frequency components, the large surface of the shaft provides amplification and good radiation possibilities. Fortunately, frequencies higher than 6 kHz are not transferred to the shaft.

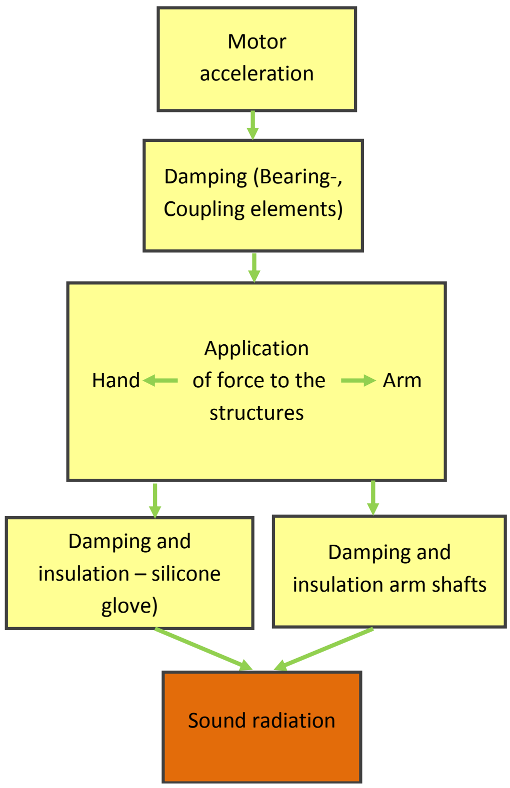

Figure 8. The vibroacustical transmission paths of the prosthesis.

To investigate the influence of the different noise components to the pleasentness of the prosthesis sound, a listening test was conducted with prosthesis users. The sounds were interactively presented to the subjects while they grasped an object. The pleasantness was evaluated on a quasi-continuous scale (0: not pleasant, 100: extremely pleasant). The investigation was conducted for two different motors M1 and M2. The noise of Motor M1 was described as loud and whining and the noise of M2 was described as scratching. The results for motor M1 show that filtering out the rotating speed dependent components, both motor and bevel gear, goes ahead with an increase of pleasentness (Fig. 9). The noise components resulting from bevel gear strengthen the machine-like character of the sound, therefore participants prefer the reduced bevel gear noise. The results for motor M2 show that high frequency components amplify the annoyance of the sound.

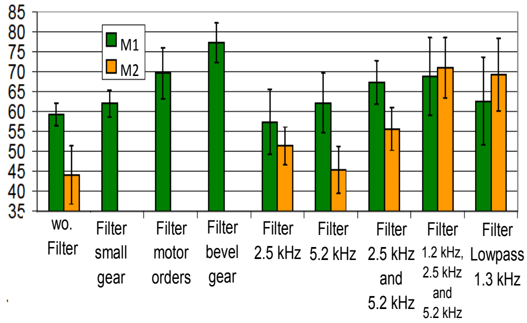

Figure 9. The pleasentness ratings of the different filtering conditions (0: not pleasant, 100: extremely pleasant).

SOUND DESIGN

After investigating the influence of the different noise components to the pleasentness of the prosthesis sound, a sound design study was conducted for prosthesis. Taking into account the interview results, the main criteria for the sound design were defined as "suitability for feedback" and "pleasentness". Information about the motion and speed of grasping activity should be delivered to the user as feedback. Therefore some natural sounds were found which can deliver this information in a pleasant way. One of them is vacuum sound (Fig. 13) and another one is the scraping sound (Fig. 10-12). The spectrum of these sounds doesn't differ strongly from original prosthesis sound, therefore it is possible to generate these sounds mechanically with some modifications on noise sources and their transfer paths (Fig. 10-13).

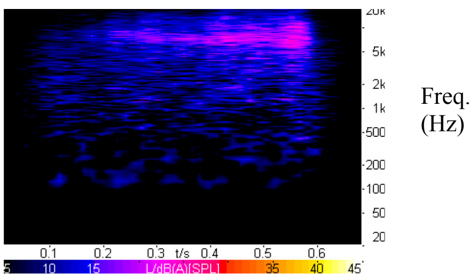

Figure 10. Spectrogram of the sound "Scraping on a felt".

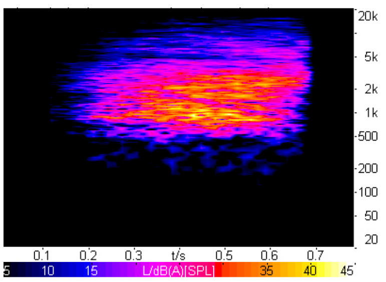

Figure 11. Spectrogram of the sound "Scraping on a paper".

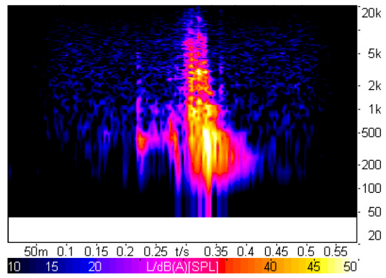

Figure 12. Spectrogram of the sound "Short impact".

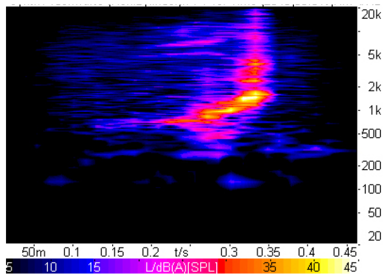

Figure 13. Spectrogram of the sound "Vacuum".

The sounds were interactively presented to the subjects while they grasped an object. The suitability as feedback and the pleasantness were evaluated on a quasi-continuous scale (0: not suitable / not pleasant, 100: extremely suitable / pleasant). The results show that vacuum sound is particularly suitable as feedback and is not perceived as annoying (Fig. 14).

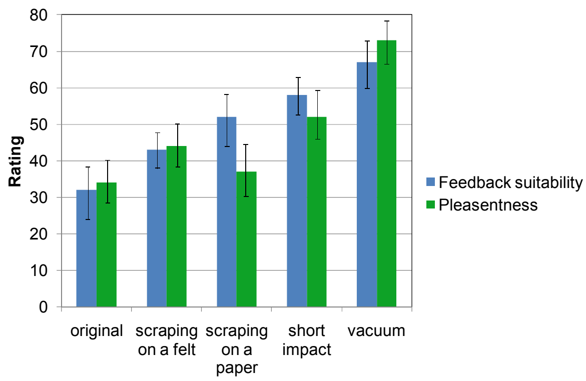

Figure 14. The feedback suitability and pleasentness ratings of the designed sounds.

CONCLUSION

This study is one of the few investigations on the vibroacoustical behavior of medical products. The results show that sound is very important to give feedback regarding grasping activity. Prosthesis users would like to have unobtrusive pleasant feedback sounds. Transfer-path-analysis allows to find sources and paths of the annoying noise components.

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