Understanding the role of the neuromuscular dynamics in biodynamic feedthrough problems

Joost Venrooij,* David A. Abbink,† Mark Mulder,‡ M.M. (René) van Paassen,§ Max Mulder¶
Delft University of Technology, Delft, The Netherlands

Biodynamic feedthrough (BDFT) refers to a phenomenon where accelerations cause involuntary limb motions which, when coupled to a control device, can result in unintentional control inputs. This study aims to increase the understanding of BDFT, and the role of the neuromuscular system (NMS) in particular. The fundamental question driving this research is how accelerations are transferred through the human body, i.e., through the NMS, and how the exact setting of the NMS influences this feedthrough. As the neuromuscular system differs from person to person and is highly adaptable, it is expected that BDFT does not only vary from person to person, but that also a single person can express a range of BDFT dynamics by adaptation of the neuromuscular settings. To investigate this hypothesis, use is made of the neuromuscular admittance, which describes the dynamic response of human limbs in response to force disturbances. A measurement method was developed to measure neuromuscular admittance and BDFT simultaneously. The results from this experiment confirm that the neuromuscular system plays such a large role in the occurrence of BDFT that the variability of the neuromuscular system cannot be ignored when investigating BDFT problems. Based on the experimental data a BDFT model was developed. The model parameters were estimated by fitting the model on the experimental data. The model successfully captures BDFT dynamics in both the frequency domain and the time domain, for different subjects and different settings of the neuromuscular system.

I. Introduction

When a human operator is subjected to accelerations while performing a control task, control performance can be degraded by the feedthrough of accelerations through the body of the human operator. This feedthrough can lead to involuntary limb motions. When coupled to a control device, these limb motions can result in unintentional control inputs, leading to control problems. This phenomenon is called biodynamic feedthrough (BDFT).

Examples of BDFT can be found in many types of vehicles, ranging from electrically-powered wheelchairs[1] to heavy hydraulic excavators and bulldozers.[2] Also aircraft are vulnerable to BDFT, where it has been identified as the cause of a phenomenon known as roll-ratcheting, a high-frequency roll oscillation that can occur during rolling maneuvers in high-performance aircraft.[3,4] Another relevant situation is one where the pilot is exposed to strong vibrations, such as in turbulence[5] or when controlling rotorcraft.[6] Note that BDFT not only plays a role when steering a vehicle but also when executing other manual control tasks while on board of a moving vehicle. The fact that BDFT can degrade manual control performance in so many ways and under so many different circumstances makes it highly relevant to study its mechanisms.

Although many studies into biodynamic feedthrough have preceded the current work,[7–11] its fundamentals are only poorly understood. Many factors have been reported to play a role and many of these show complex mutual interactions. What makes BDFT particularly challenging is the role of the human operator. The human operator is not only a very complex system, it is also highly adaptive. When adapting to new circumstances or when changing behavior

*PhD Researcher, Control and Simulation Division, Faculty of Aerospace Engineering, Delft University of Technology. Kluyverweg 1, 2629 HS Delft, The Netherlands. E-mail: j.venrooij@tudelft.nl

†Researcher, Biomechanical Engineering Division, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology. Mekelweg 2, 2628 CD Delft, The Netherlands. E-mail: d.a.abbink@tudelft.nl

‡Researcher, Control and Simulation Division, Faculty of Aerospace Engineering, Delft University of Technology. Kluyverweg 1, 2629 HS Delft, The Netherlands. E-mail: mark.mulder@tudelft.nl

§Associate Professor, Control and Simulation Division, Faculty of Aerospace Engineering, Delft University of Technology. Kluyverweg 1, 2629 HS Delft, The Netherlands. E-mail: m.m.vanpaassen@tudelft.nl

¶Professor, Control and Simulation Division, Faculty of Aerospace Engineering, Delft University of Technology. Kluyverweg 1, 2629 HS Delft, The Netherlands. E-mail: m.mulder@tudelft.nl

the human operator changes the way he/she interacts with the environment. Think for example of a pilot relaxing or tightening his grip on the control stick. Evidently, this changes the way accelerations are transferred from the body to the stick, resulting in a change in BDFT dynamics.

What differentiates the current study from many of the preceding studies is the particular focus that is put on the role of the neuromuscular system (NMS) in BDFT problems. The fundamental question driving this research is how accelerations are transferred through the human body, i.e., through the NMS, and how the exact setting of the NMS influences this feedthrough. It has been observed that differences in musculature and/or posture results in differences in BDFT for different subjects (inter-subject variability).[10] However, this study contributes to the existing knowledge by investigating the hypothesis that also a single person can express a range of biodynamic feedthrough dynamics due to adaptation of his/her neuromuscular settings (intra-subject variability). Evidently, understanding this intra-subject variability is essential in the understanding and modeling of biodynamic feedthrough problems in practice. In a later stage, the knowledge on the role of the NMS in BDFT can be applied in the development of advanced methods of BDFT-canceling in actual vehicles.

To investigate the role of the NMS, use is made of neuromuscular admittance. Neuromuscular admittance describes the dynamic response of human limbs in response to force disturbances, by providing the dynamic relation between a force input and a position output. The approach taken in this study is to measure neuromuscular admittance and biodynamic feedthrough simultaneously. The results allow for investigating the influence of the setting of the NMS on BDFT. Based on the experimental data a model was constructed that describes both neuromuscular admittance and biodynamic feedthrough. To develop this model, use was made of an already existing and well-studied neuromuscular model.[12] The current paper aims to show the necessity and traits of taking knowledge of the neuromuscular system into account when investigating BDFT problems. Detailed description of the measurement method and the BDFT model will be dealt with in future publications.

The structure of this paper is as follows: first, in Section II, the approach of this BDFT study is addressed. The work presented in this paper consists of two parts, namely the measurement of BDFT and the development of a BDFT model. The sections are organized to reflect this structure, so each section, after Section II, contains one paragraph devoted to measuring and one devoted to modeling. Section III elaborates on the methods used to measure and model biodynamic feedthrough. The results of both the measuring and modeling efforts are shown in Section IV. Finally, Section V contains the conclusions.

II. Current approach

II.A. Biodynamic feedthrough system

The diversity in the situations and vehicles where biodynamic feedthrough can occur calls for a general representation of the BDFT problem; a system representation in which BDFT is captured in a general form. Such a representation is proposed in the following.

Figure 1 shows a schematic representation of the general biodynamic feedthrough system. In this representation, four main elements can be identified. The human operator (HO) acts as a controller in a manual control task. The HO is controlling the (partial) state of a controlled element (CE) by comparing the current state Y_{cur} with a certain goal state Y_{goal}. The CE can be disturbed by a disturbance signal, for which the HO is requested to compensate. The HO can influence the state of the CE by means of a control device (CD). Control commands are applied by exerting a force, labeled the contact force, F_C, on the CD, resulting in a control input signal, θ_{CD}, that in turn enters the CE. The HO and the CD are connected to a platform (PLF), which is a moving, physical object, typically a vehicle. The acceleration signal coming from the PLF is called the motion disturbance signal M_{dist}, which can be used to identify the biodynamic feedthrough. The neuromuscular admittance can be identified using a force disturbance on the stick,[13] labeled F_{dist}. Note that F_{dist} is not part of the biodynamic feedthrough problem itself, but necessary to determine the neuromuscular admittance of the human operator. It is assumed that the force disturbance does not correlate with the remnant in the control signal.[14] Biodynamic feedthrough occurs when the motion disturbances induce unintentional motions in the limb that is in contact with the CD, thereby leading to unintentional control inputs. In that case, the control input signal θ_{CD} consists of the following contributions:

$$\theta_{CD}(t) = \theta_{CD}^{cog}(t) + \theta_{CD}^{Fdist}(t) + \theta_{CD}^{Mdist}(t) + \theta_{CD}^{res}(t), \tag{1}$$

where the superscript cog denotes the cognitive element in the control device deflection, i.e, the part that is due to voluntary control actions. The superscript F_{dist} denotes the contribution of the force disturbance and M_{dist} the contribution of the motion disturbance (the biodynamic feedthrough). The remaining part of the control input signal,

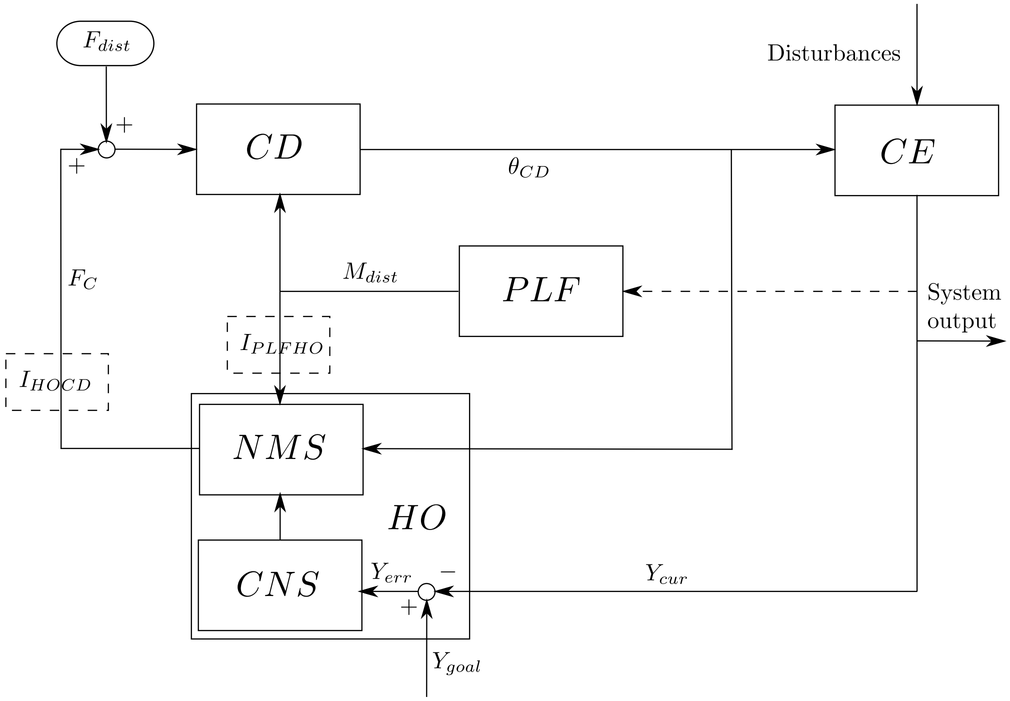

Figure 1. Schematic representation of the general biodynamic feedthrough system.

the part that is not related to a disturbance signal or cognitive control, is here labeled as the residual and denoted by the superscript res. Evidently, for the contact force F_C the same holds:

$$F_C(t) = F_C^{cog}(t) + F_C^{Fdist}(t) + F_C^{Mdist}(t) + F_C^{res}(t). \tag{2}$$

The feedthrough of PLF accelerations via the body of the HO into the CD is governed by two 'interfaces'. These interfaces describe the dynamics between the human operator and the environment and are indicated in Figure 1 by the dashed boxes, I_{PLFHO} and I_{HOCD}. The interface I_{PLFHO} describes the dynamics of the connection between the PLF and the HO, e.g., seat damping or the effect of seat belts. The dynamics of this interface determine how accelerations enter the body of the operator. The interface I_{HOCD} describes the dynamics of the connection between HO and CD, e.g., grip visco-elasticity or the effect of an arm rest. This interface determines how limb motions result in contact forces F_C. Note that I_{PLFHO} plays a role in the BDFT dynamics only and I_{HOCD} plays a role in both the admittance dynamics as well as the BDFT dynamics.

The human operator model can be split in the central nervous system (CNS), and the neuromuscular system (NMS). The CNS is responsible for all cognitive control commands ($\theta_{CD}^{cog}(t)$) that are neurally communicated to the NMS. The NMS represents the neuromuscular system of the arm connected to the control device and contains body elements such as bones, muscles, etc.

The case of a pilot controlling an aircraft in turbulence can be used as an example to clarify the biodynamic feedthrough system in Figure 1. In this case the pilot (HO), is controlling the aircraft (CE), by using a control column or side-stick (CD). The PLF is in this case also the aircraft, or, more precisely, the seat the pilot is sitting in. The accelerations of the aircraft transfer into the body of the pilot through the seat (I_{PLFHO}) and cause involuntary limb motions. As the pilot is holding the control stick these motions are transferred into the stick (through I_{HOCD}) and contribute to the control device deflection angle θ_{CD}.

Now consider a co-pilot, who is also on board of this aircraft, but currently not involved in controlling the aircraft. The co-pilot is executing a different task, say, pointing a camera. Also in this case the PLF is the aircraft, but the co-pilot is controlling a different CE, namely the camera. The fact that the HO can be on board of a vehicle, but controlling a different system is the reason for introducing both the CE and the PLF. The case of the co-pilot is called an open-loop BDFT system, where there exists no connection between the CE and the PLF. The case of the pilot is a so called closed-loop BDFT system, where there is some sort of (direct or indirect) connection between CE and PLF. To account for these two types of BDFT systems, the connection between PLF and CE is indicated with a dotted line.

II.B. Scope of the current research

Not all aspects of the BDFT system discussed above are of importance for the current study. The scope of the research is limited by the following aspects:

- The current research focuses on the neuromuscular aspect of BDFT, thus on the role of the NMS part of the human operator only; cognitive control actions are not considered;
- In this study only open-loop BDFT systems are investigated. No influence of the human operator on the PLF motion is assumed;
- The investigation deals with the occurrence of BDFT in general and not for any vehicle in particular. Therefore, the dynamics of the PLF or the CE are secondary to our objectives;
- In this study only lateral accelerations are investigated for control tasks using a side-stick.

Using the above considerations, the BDFT system displayed in Figure 1 can be reduced to a form that is relevant for the current research. As only open-loop systems are considered, the dotted line in Figure 1 can be removed. No cognitive inputs are considered, so the contents of the CNS block is not investigated in this study. Finally, as the dynamics of the controlled element and platform are secondary to our objectives, also the CE block and the PLF block lie outside the scope of this investigation. What remains from the BDFT system that is of importance for the current study are the disturbance signals F_{dist} and M_{dist}, the NMS block, the CD block, and the two interfaces.

II.C. Measuring, modeling and canceling biodynamic feedthrough

BDFT can be induced by perturbing the body of a subject with a motion disturbance signal M_{dist} in a motion-based simulator. The neuromuscular admittance can be determined by imposing a force disturbance signal, F_{dist}, on the control device. By measuring the control device deflections and the forces applied by the operator, both the biodynamic feedthrough and admittance can be estimated. For the estimation of the neuromuscular admittance use is made of known techniques, for example described in Ref. 14. The techniques to estimate the BDFT are very similar, as shown in section III.A.7.

The BDFT system in Figure 1 can be used to develop a BDFT model. A BDFT model describes the influence of motion disturbances on control device deflections, hence the feedthrough of M_{dist} to θ_{CD}. The relevant system parts for a BDFT model can be easily identified by following the path from M_{dist} to θ_{CD} in Figure 1. The elements that need to be included in the BDFT model are: the interface I_{PLFHO}, the neuromuscular system NMS, the interface I_{HOCD} and the control device CD.

Once an accurate model is obtained, it can be employed to cancel biodynamic feedthrough. The model serves to determine the involuntary, vibration induced, part in either F_C or θ_{CD}. By canceling this part in the actual control input, an efficient and effective way of canceling biodynamic feedthrough is obtained.

III. Methods

III.A. Measuring biodynamic feedthrough

III.A.1. Apparatus

The experiment was performed on the SIMONA Research Simulator (SRS)[15] of Delft University of Technology, a six degree-of-freedom flight simulator. The control device was an electrically actuated side-stick. No arm rest for the arm that controlled the side-stick was present. The seat in which the subjects were seated had a 5-point safety belt that was adjusted tightly.

III.A.2. Subjects

Five subjects (3 male, 2 female, average age of 26 years, and a standard deviation of 3 years) participated in the experiment. Subjects were recruited from the student population of Delft University of Technology.

III.A.3. Task instruction

The subjects performed three different disturbance-rejection tasks:[16] a position task (PT), with the instruction to resist all perturbations (minimize position of stick), a force task (FT), with the instruction to yield to all perturbations (minimize force applied to stick), and a relax task (RT), with the instruction to relax the arm. The human operator needed to set his/her neuromuscular properties differently for optimal control of each of the three control tasks.

III.A.4. Procedure

During the experiments the side-stick was perturbed with the lateral force disturbance signal F_{dist}. Simultaneously with the force disturbance signal, the lateral motion disturbance signal M_{dist} was used to induce biodynamic feedthrough. During the PT and FT, information was displayed on a 15" LCD screen in front of the subjects. During the position task the lateral side-stick deflection angle was displayed against the target deflection (0 deg), during the force task the applied force to the side-stick was shown against the target force ($0N$). During the relax the display presented no information.
Before entering the simulator the subjects were instructed on the goal of the experiment and the control tasks they were to perform. Several training runs were performed to allow the subject to get used to the disturbances and the different control tasks. When the subjects indicated to have understood the control tasks the measurements started.
The control tasks were performed in the order PT-RT-FT and four repetitions of this sequence were executed. For reference purposes, three repetitions of the same control tasks (also in the order PT-RT-FT) were executed without the motion disturbance signal present. The latter condition will be referred to as the static condition, and the first as the motion condition. Note that in the static condition no biodynamic feedthrough was present and only the admittance was measured. For this study it was assumed that the influence of learning effects was negligible.

III.A.5. Perturbation signal design

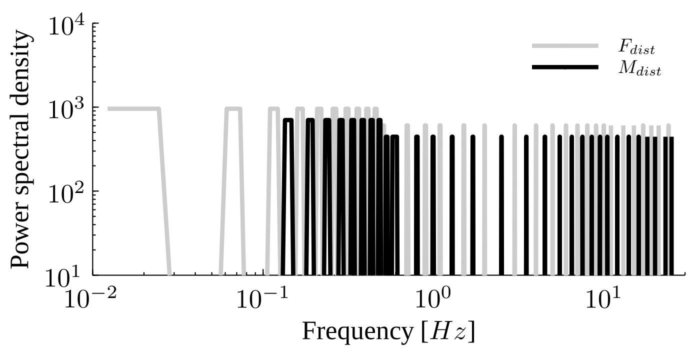

Figure 2. Power spectral density plot of disturbance signals F_{dist} and M_{dist}.

Both disturbance signals were multi-sines, defined in the frequency domain. The signals were separated in frequency, see Figure 2, to allow distinguishing the response due to each disturbance in the measured signals.[17] To obtain a full bandwidth estimate of the admittance, a range between 0.01 Hz and 24 Hz was selected for the force disturbance signal F_{dist}. This is a sufficient bandwidth to capture all arm dynamics.[18] For the motion disturbance signal M_{dist}, a range between 0.15 and 25 Hz was selected. For both disturbance signals, 31 logarithmically spaced frequency points were selected in the frequency range, without overlap between the two disturbance signals. To allow for frequency averaging, power was applied to two adjacent frequency points for each point,[19] yielding 31 pairs of frequency points for each disturbance signal.
The phase of the sine components was randomized in order to obtain an unpredictable signal. To allow estimation of full-bandwidth dynamics, without influencing the low-frequency behavior, the reduced power method[20] was used to construct the disturbance signals.

III.A.6. Recordings

During the experiments the angular deflection of the side-stick θ_{CD}, and the applied force to the side-stick F_C were measured. The disturbance signals were recorded.

III.A.7. Non-parametric identification

The admittance was estimated in the frequency domain, using a closed loop identification technique using the estimated cross-spectral density between F_{dist} and θ_{CD} ($\hat{S}_{fd-\theta}$) and the estimated cross-spectral density between F_{dist} and F_C ($\hat{S}_{fd-f}$):[14]

$$\hat{H}_{adm}(w_f) = \frac{\hat{S}_{fd-\theta}(w_f)}{\hat{S}_{fd-f}(w_f)}, \tag{3}$$

where w_f are the frequencies of the force disturbance signal F_{dist}.
The procedure assumes linearity. To check the reliability of this assumption the squared coherence $\hat{\Gamma}^2_{adm}$ was calculated:

$$\hat{\Gamma}^2_{adm}(w_f) = \frac{\left|\hat{S}_{fd-\theta}(w_f)\right|^2}{\hat{S}_{fd-fd}(w_f)\hat{S}_{\theta-\theta}(w_f)} \tag{4}$$

In a very similar way the transfer function describing the biodynamic feedthrough dynamics H_{bdft} can be estimated. The estimate of the biodynamic feedthrough dynamics $\hat{H}_{bdft}$, is calculated using the estimated cross-spectral density between M_{dist} and θ_{CD} ($\hat{S}_{md-\theta}$) and the estimated auto-spectral density of M_{dist} ($\hat{S}_{md-md}$)

$$\hat{H}_{bdft}(w_m) = \frac{\hat{S}_{md-\theta}(w_m)}{\hat{S}_{md-md}(w_m)}, \tag{5}$$

where w_m are the frequencies of the motion disturbance signal M_{dist}.
And the squared coherence function in this case:

$$\hat{\Gamma}^2_{BDFT}(w_m) = \frac{\left|\hat{S}_{md-\theta}(w_m)\right|^2}{\hat{S}_{md-md}(w_m)\hat{S}_{\theta-\theta}(w_m)} \tag{6}$$

III.B. Modeling biodynamic feedthrough

III.B.1. Neuromuscular model

Modeling of biodynamic feedthrough was done by using a neuromuscular model as a starting point. The neuromuscular model used in this study is elaborately described in Ref. 12. For our current purposes – showing how this model can be used in BDFT modeling – it suffices to discuss the model in a simplified mechanical representation, as shown in Figure 3. The model consists of two parts, one represents the neuromuscular admittance and one the control device dynamics. The control device is modeled as a mass-spring-damper system (CD). The human arm, with mass m_{arm}, is connected to the control device by grip dynamics, represented by a spring and a damper. The intrinsic neuromuscular dynamics are represented by yet another spring and damper (NMS). The model also includes reflexive properties, which are not shown in full detail for the sake of simplicity. The force disturbance F_{dist}, imposed on the control device mass, is used to estimate the neuromuscular admittance.

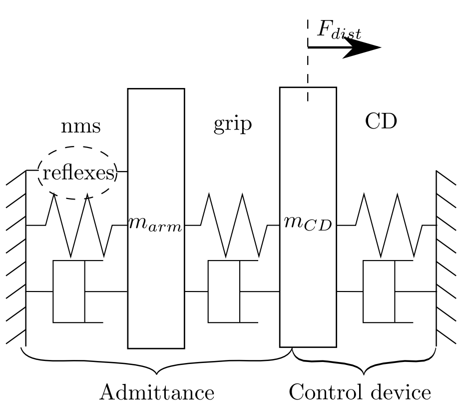

Figure 3. Neuromuscular model

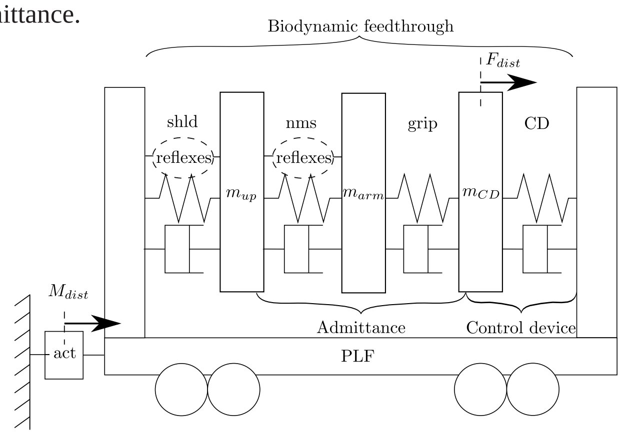

Figure 4. BDFT model, obtained by augmenting the neuromuscular model

III.B.2. Biodynamic feedthrough model

The approach taken in this study is to expand the neuromuscular model to include the effects of biodynamic feedthrough. The representation in Figure 3 depicts an insightful way of deriving such a model. A fist step in including the effect of motion is to allow the combination of the human arm and control device to move with respect to the environment, under the influence of the motion disturbance M_{dist}. This can be represented by situating the combination of the mass-spring-damper systems in Figure 3 on a platform PLF, that is allowed to move under a motion disturbance M_{dist}. In this study, only lateral motion disturbances are considered, and the model is thus limited to describe motions in lateral direction only. For the feedthrough of disturbances in this direction, the sideways motion of the torso (with respect to the seat) and sideways motion of the upper arm (rotation around the shoulder joint) are most relevant. In this study the motion of the torso was assumed to be small. The upper arm was modeled in basically an identical way as the (fore) arm was modeled in the neuromuscular model. This can be represented by adding a similar mass-spring-damper system (including reflexes) to the left of the one already present in Figure 3. Now we have obtained a model that accounts for the effects of biodynamic feedthrough.
Figure 4 shows the BDFT model, the elements representing the upper arm are shown on the left. The spring and damper represent the stiffness and damping of the shoulder joint (shld). The mass, m_{up}, represents the mass of the upper arm that is excited by the platform motions. Just as in the neuromuscular model, reflexive activity was added to account for the reflexive activity present in the muscles excited during BDFT. Motion disturbances were added by situating the combination of mass-spring-damper systems on a platform PLF. The dynamics that were added to account for the effect of motion disturbances will be referred to as the 'additional dynamics'. The combination of control device dynamics, neuromuscular dynamics and the additional dynamics are the biodynamic feedthrough dynamics.

III.B.3. Model validation

A parameter estimation technique was developed to fit the model on a measured responses in the frequency domain. The techniques used to estimate the parameters of the model will be described in future publications.
To validate the obtained results in the time domain, use was made of the Variance Accounted For (VAF).[17] The VAF gives a measure of the match between two time signals. The VAF was calculated from the difference between the modeled control device deflection $\hat{\theta}_{CD}$ and the measured control device deflection θ_{CD}:

$$VAF = \left[1 - \frac{\sum_{k=1}^{N} \left[\theta_{CD}(t_k) - \hat{\theta}_{CD}(t_k) \right]^2}{\sum_{k=1}^{N} \left[\theta_{CD}(t_k) \right]^2} \right] 100\%. \tag{7}$$

A VAF of 100% means that the model fully describes the system response. Lower values indicate mismatches in the model fit and/or the presence of noise.

IV. Results

IV.A. Measuring admittance and biodynamic feedthrough

IV.A.1. Neuromuscular admittance

Figure 5 shows the means (lines) and standard deviations (gray bands) of the non-parametric admittance estimates of a typical subject. As expected, for low frequencies the admittance is the highest for the force task and the lowest for the position task. At higher frequencies the differences become smaller as dynamics are more and more governed by inertia. The admittance measured for the relax task lies between the one measured for the force task and the position task, which is in agreement with expectations. However, for several subjects the difference between the admittance measured in the relax task and the force task shows to be smaller than expected. A possible explanation of this is that the scaling of the force gain in the relax tasks was set too high, yielding too large control device deflections relative to the two other tasks. Another possible explanation lies in the task instruction and execution. Although some time for training was scheduled, some subjects indicated after the experiment to have had difficulty distinguishing between tasks, especially between the FT and the RT.
High squared coherences, a measure for reliability of the estimate, were found at all frequencies for all tasks (except for the lowest frequency). Furthermore, the results were found to be comparable with the results of a previous study.[13]

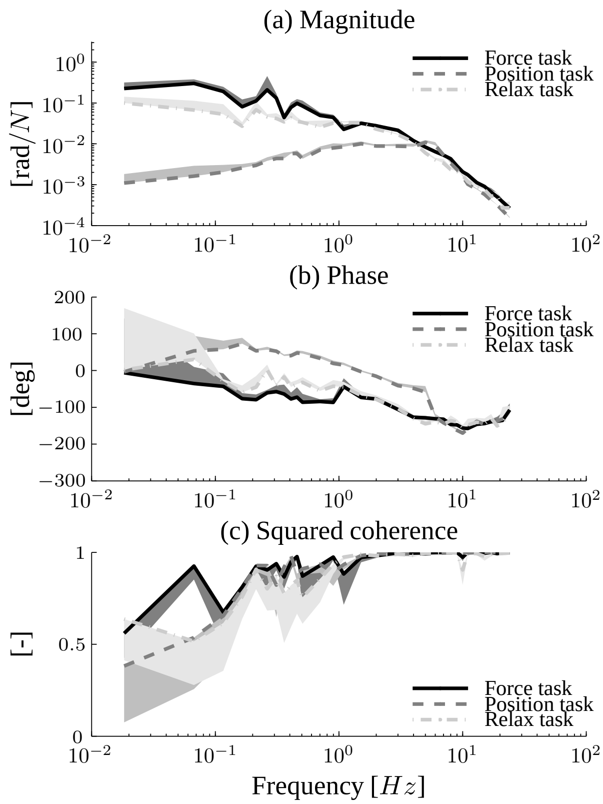

Figure 5. Neuromuscular admittance estimate for a typical subject

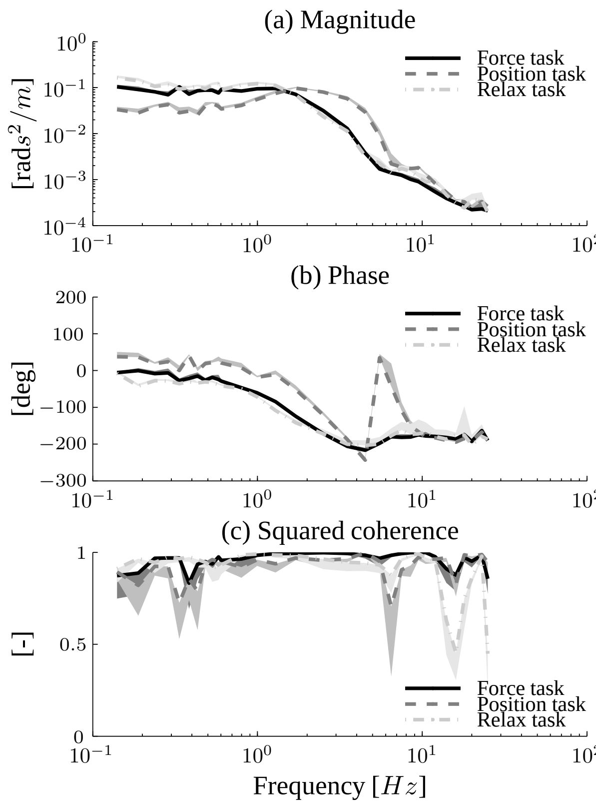

Figure 6. Biodynamic feedthrough estimate for a typical subject

Taking the above considerations into account, it can be said that in general the results are in good agreement with both expectations and previous research.

IV.A.2. Biodynamic feedthrough

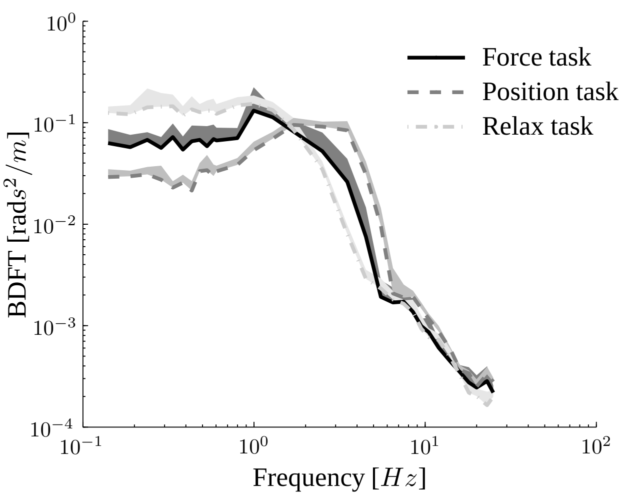

Figure 7. Biodynamic feedthrough magnitude, averaged over all subjects

Figure 6 shows means (lines) and standard deviations (gray bands) the non-parametric biodynamic feedthrough estimates for a typical subject, measured simultaneously with the admittance shown in Figure 5. It can be seen that for the three different task instructions, different BDFT dynamics were measured. Due to the experiment setup, the differences in BDFT are most likely explained by adaptations of the neuromuscular system by the human operator in response to task instruction. Hence, we can conclude that biodynamic feedthrough depends on task instruction, and thus on the neuromuscular admittance.

The reliability of the measurement is reflected in the high squared coherences found for all frequencies. The BDFT dynamics measured for the other subjects were comparable to the ones shown in Figure 6. Figure 7 shows the the biodynamic feedthrough magnitude for the three control tasks, but now averaged over all subjects. The figure shows that a similar dependency of biodynamic feedthrough on task instruction (and thus on the setting of the NMS system) was observed across subjects.

For low frequencies, the BDFT is the lowest for the PT. This is in line what is to be expected from the character of this control task, i.e., the feedthrough of low-frequency accelerations is best attenuated by being ’stiff’. Surprisingly, for frequencies higher than approximately 1.5 Hz, the BDFT of the PT is higher than for the other tasks. Moreover, a peak in BDFT is observed for the PT between approximately 2-3 Hz. This result is remarkable and suggest that being 'stiff' leads to an increase in the feedthrough of motion disturbances above 1.5 Hz, in comparison to the other control tasks.

IV.B. Modeling biodynamic feedthrough

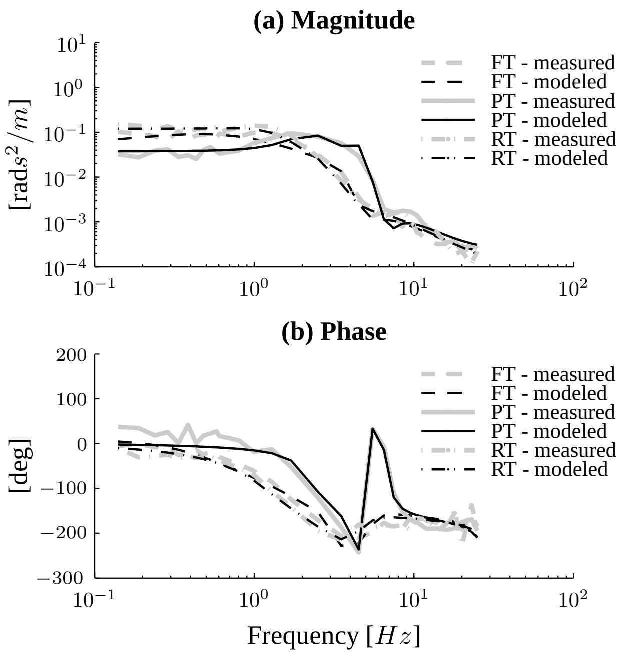

Figure 8. Fit of the BDFT model on the measured data for a typical subject

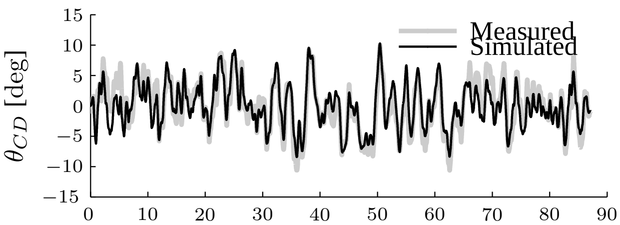

Figure 9. Comparison of the measured response with the simulated response for a FT

The BDFT model was fitted to the measured biodynamic feedthrough in the frequency domain. The result for a typical subject is shown in Figure 8. It can be observed that the features of the measured BDFT dynamics are well described by the BDFT model. Both the measured and modeled response differ for each task, i.e., each setting of the neuromuscular system. This shows the necessity of understanding and accounting for the role of the neuromuscular system in BDFT models. Assuming a static BDFT model, as was done in some previous studies,[1,2,21] can yield accurate results, but only for one setting of the NMS at best. These models lack the capability to cope with the inherent adaptability of the human operator's neuromuscular system, and so the variability in e.g., grip strength, muscle tension or posture.

To validate the quality of the model in the time domain, the model was used to simulate the response θ_{CD}. An example of how the simulated response of the BDFT model matches with the measured response is shown in Figure 9 (for a force task). This shows that many features in the measured response are accurately described by the simulated response. This was observed for the other task instructions as well. Using VAF, the performance of the model in the time domain can be quantified. The results are shown in Table 1. The first and second column show the result obtained when using the neuromuscular model in the static conditions and the motion condition. It can be observed that in the motion condition the VAFs decrease considerably with respect to the static condition. This signifies that the addition of a motion disturbance affects the measured response in a way that cannot be accounted for by the neuromuscular model. To 'restore' the VAFs the BDFT model needs to used, as this model does take the effects of the motion disturbance into account. The results of using this model are shown in the rightmost column of Table 1. When compared to the VAFs obtained by the neuromuscular model in the motion condition, a significant improvement can be observed when using the BDFT model. In fact, the results approximate the results obtained using the neuromuscular model in the static condition. This indicates that the BDFT model succeeded in capturing the effect of both the force and the motion disturbances in the time domain.

Table 1. Mean and standard deviation of the VAF for the NMS model and for the BDFT model

	Neuromuscular model		BDFT model
	Static condition	Motion condition	
Task	VAF (SD) [%]	VAF (SD) [%]	VAF (SD) [%]
FT	73.90% (12.76)	28.41% (13.8)	64.93% (15.5)
PT	76.97% (3.0)	50.24% (4.7)	61.71% (6.0)
RT	77.48% (14.0)	40.06% (16.1)	82.7% (5.2)

V. Discussion and conclusions

This study aims to increase the understanding of the role of the neuromuscular system in biodynamic feedthrough. The fundamental question driving this research is how accelerations are transferred through the human body, i.e., through the NMS, and how the exact setting of the NMS influences this feedthrough. As the neuromuscular system differs from person to person and is highly adaptable, it is expected that BDFT does not only vary from person to person, but that also a single person can express a range of BDFT dynamics by adaptation of the neuromuscular settings. The results of an experiment where neuromuscular admittance and BDFT were measured simultaneously confirm this hypothesis. It can be concluded that the neuromuscular system plays such a large role in the occurrence of BDFT that the variability of the neuromuscular system cannot be ignored when investigating BDFT problems.

V.A. Measuring biodynamic feedthrough

A measurement method is proposed to measure neuromuscular admittance and biodynamic feedthrough simultaneously. For the studied experimental conditions, it was concluded that the proposed measurement method was successful. The admittance measurements are comparable to the results found in other studies in which admittance was measured during side-stick control.[13] High coherences indicate that the admittance estimates are reliable. Also for the BDFT measurements, high coherences were found, indicating the BDFT estimates are reliable. Furthermore, between subjects, each task shows BDFT dynamics with comparable shape and features. Differences observed in BDFT for the different control tasks are most likely caused by adaptations of the neuromuscular system. Hence, it can be concluded that there exists a dependency of biodynamic feedthrough on neuromuscular admittance, something that was not reported in many other BDFT studies.

The non-parametric results provide some insights in the occurrence of BDFT in practice. In Figure 7 it can be observed that the feedthrough of low-frequency accelerations ($< 1.5\ Hz$) is the lowest in the PT, i.e. when the human operator is 'stiff'. However, for frequencies between than 1.5 Hz and 6 Hz, the BDFT is higher for the 'stiff' setting than for the other settings of the NMS. In other words, in this frequency range, being 'stiff' results in more involuntary control inputs than being more compliant. When applying this insight to a practical example of a pilot flying in turbulence, it becomes clear that when the pilot tightens the grip on the stick in response to the disturbances (which is a likely natural response), this only reduces the feedthrough of the low-frequency component of the turbulence. The level of feedthrough of disturbances above 1.5 Hz is, in fact, higher than when the pilot would relax his grip on the stick. In a previous study[5] it was already reported that pilots experienced BDFT effects in this frequency range by involuntary coupling with one of the aircraft's structural modes and that 'the tendency appeared to increase when pilots tightened their grip on the stick'. With the results presented in this paper this observation is experimentally confirmed.

V.B. Modeling biodynamic feedthrough

The model proposed in this article makes use of a neuromuscular model and additional dynamics to describe biodynamic feedthrough. The motivation for using a neuromuscular model is the dependency of biodynamic feedthrough on neuromuscular admittance. The model was validated by fitting it on measurement data. The model successfully captures BDFT dynamics in both frequency and time domain, for different subjects and different settings of the neuromuscular system. Similar results were found across subjects.

In practice, the human operator will adapt the settings of his neuromuscular system based on the current task and circumstances. Modeling the occurrence of BDFT in these cases requires and adaptive model that accounts for the dependency between the neuromuscular system and the occurrence of BDFT. Especially when employing the model in practice for model-based BDFT-cancellation, the variability of the neuromuscular system cannot be ignored.

V.C. Future work

Currently, research efforts are being devoted to refining the model that is introduced this paper. An elaborate description of the content and parameterization of the model will be presented in future publications. One of the issue that will be dealt with is the evaluation and validation of the model's parameter values. Closely related to this is the discussion on the physical interpretability of the proposed model (do all the model parameters represent physical quantaties?). Furthermore, the risk of overparameterization of the model and the required countermeasures will be addressed, by making use of some of the techniques described in Ref. 22. The refined model can be used to investigate the relation between biodynamic feedthrough and neuromuscular admittance. It is expected that there exists a relation between some NMS parameters and some BDFT parameters. If strong relationships prove to exist, it might be possible to obtain a reliable BDFT model by measuring neuromuscular properties only. One of the possibilities that will be explored is how the integration of some easily measured quantities, such as grip force, can simplify the parameterization of the BDFT model. This could yield interesting applications in the model-based cancellation of biodynamic feedthrough.

References

[1] Banerjee, D., Jordan, L. M., and Rosen, M. J., "Modeling the effects of inertial reactions on occupants of moving power wheelchairs," *Proceedings of the Rehabilitation Engineering and Assistive Technology Society of North America Conference (RESNA)*, 1996, pp. 220–222.

[2] Arai, F., Tateishi, J., and Fukuda, T., "Dynamical analysis and suppression of human hunting in the excavator operation," *9th IEEE International Workshop on Robot and Human Interactive Communication, RO-MAN, Osaka, Japan*, 2000, pp. 394–399.

[3] Höhne, G., "A biomechanical pilot model for prediction of roll ratcheting," *AIAA Atmospheric Flight Mechanics Conference and Exhibit, Portland, OR, United States*, Aug 1999, pp. 187 – 196.

[4] Hess, R. A., "Theory for roll-ratchet phenomenon in high-performance aircraft," *Journal of Guidance, Control and Dynamics*, Vol. 21, No. 1, 1998, pp. 101–108.

[5] Raney, D. L., Jackson, E. B., Buttrill, C. S., and Adams, W. M., "The impact of structural vibrations on flying qualities of a supersonic transport," *AIAA Atmospheric Flight Mechanics Conference*, August 2001.

[6] McRuer, D. T., "Interdisciplinary interactions and dynamic system integration," *International Journal of Control*, Vol. 59, No. 1, 1994, pp. 3 – 12.

[7] Allen, R. E., Jex, H. R., and Magdaleno, R. E., "Manual control performance and dynamics response during sinusoidal vibration," *AMRL-TR-73-78*, 1973.

[8] Jex, H. R. and Magdaleno, R. E., "Biomechanical models for vibration feedthrough to hands and head for a semisuspine pilot," *Aviation, Space, and Environmental Medicine*, Vol. 49, No. 1, 1978, pp. 304 – 316.

[9] McLeod, R. W. and Griffin, M. J., "Review of the effects of translational whole-body vibration on continuous manual control performance," *Journal of Sound and Vibration*, Vol. 133, No. 1, 1989, pp. 55 – 115.

[10] Sövényi, S., *Model-based cancellation of biodynamic feedthrough with a motorized manual control interface*, Ph.D. thesis, University of Michigan, 2005.

[11] Demic, M. and Lukic, J., "Investigation of the transmission of fore and aft vibration through the human body," *Applied Ergonomics*, Vol. 40, 2009, pp. 622–629.

[12] Schouten, A. C., Mugge, W., and van der Helm, F. C. T., "NMClab, a model to assess the contributions of muscle visco-elasticity and afferent feedback to joint dynamics," *Journal of Biomechanics*, Vol. 41, 2008, pp. 1659 – 1667.

[13] Lasschuit, J., Lam, T. M., Mulder, M., van Paassen, M. M., and Abbink, D. A., "Measuring and modeling neuromuscular system dynamics for haptic interface design," *AIAA Modeling and Simulation Technologies Conference and Exhibit, Honululu, Hawaii*, 2008, pp. 304 – 316.

[14] van der Helm, F. C. T., Schouten, A. C., de Vlugt, E., and Brouwn, G. G., "Identification of intrinsic and reflexive components of human arm dynamics during postural control," *Journal of Neuroscience Methods*, Vol. 119, 2002, pp. 1–14.

[15] Stroosma, O., van Paassen, M. M., and Mulder, M., "Using the simona research simulator for human-machine interaction research," *Proceedings of the AIAA Modeling and Simulation Technologies Conference and Exhibit, Austin, Texas*, 2003.

[16] Abbink, D. A., *Neuromuscular analysis of haptic gas pedal feedback during car following*, Ph.D. thesis, Delft University of Technology, 2006.

[17] Nieuwenhuizen, F. M., Zaal, P. M. T., Mulder, M., van Paassen, M. M., and Mulder, J. A., "Modeling human multichannel perception and control using linear time-invariant models," *Journal of Guidance, Control, and Dynamics*, Vol. 31, No. 4, 2008, pp. 999–1013.

[18] Perreault, E. J., Kirsch, R. F., and Crago, P. E., "Effects of voluntary force generation on the elastic components of endpoint stiffness," *Experimental Brain Research*, Vol. 141, 2001, pp. 312–323.

[19] Schouten, A. C., de Vlugt, E., and van der Helm, F. C. T., "Design of perturbation signals for the estimation of proprioceptive reflexes," *IEEE Trans. Biomed. Eng.*, Vol. 55, No. 5, 2008, pp. 1612 – 1619.

[20] Mugge, W., Abbink, D. A., and van der Helm, F. C. T., "Reduced power method: how to evoke low-bandwidth behaviour while estimating full-bandwidth dynamics," *IEEE 10th International Conference on Rehabilitation Robotics. ICORR*, 2007, pp. 575 – 581.

[21] Sövényi, S. and Gillespie, R. B., "Cancellation of biodynamic feedthrough in vehicle control tasks," *IEEE Trans. Control Syst. Technol.*, Vol. 15, No. 6, 2007, pp. 1018 – 1029.

[22] Mugge, W., Abbink, D. A., Schouten, A. C., Dewald, J. P. A., and van der Helm, F. C. T., "A rigorous model of reflex function indicates that position and force feedback are flexibly tuned to position and force tasks," *Experimental Brain Research*, 2009.