2012 IEEE International Conference on Systems, Man, and Cybernetics
October 14-17, 2012, COEX, Seoul, Korea

How effective is an armrest in mitigating biodynamic feedthrough?

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***Abstract*—Biodynamic feedthrough (BDFT) refers to a phenomenon where vehicle accelerations feed through the human body, causing involuntary limb motions, which may cause involuntary control inputs. Many studies have been devoted to mitigating BDFT effects. In the current paper, the effectiveness of a simple, cheap and widely-used hardware component is studied: the armrest. An experiment was conducted in which the BDFT dynamics were measured with and without armrest for different levels of neuromuscular admittance (i.e., different settings of the limb dynamics). The results show that the effect of the armrest on BDFT dynamics varies, both with frequency and neuromuscular admittance.**

***Index Terms*—biodynamic feedthrough, neuromuscular admittance, manual control, biodynamic feedthrough mitigation**

I. Introduction

Biodynamic feedthrough (BDFT) refers to a phenomenon where vehicle accelerations feed through the human body, leading to involuntary motion of body parts as head, torso, arms, hands and legs. Involuntary bodily motion is not only a nuisance, it may also cause manual control problems during the execution of a manual control task, by generating involuntary control inputs [1]. The fact that BDFT reduces ride comfort, control performance and – above all – safety during vehicle operation makes it an interesting research topic. Different aspects of the BDFT phenomenon were investigated in literature. In some studies, BDFT effects were measured (e.g., [1]) or modeled (e.g., [2]). Others discuss mitigating BDFT effects (e.g., [3]), which is the focus of the current paper.

An early publication regarding BDFT mitigation is by Schubert et al. [4] where the effectiveness was studied of isolating the human operator from vehicle accelerations. Velger et al. proposed an adaptive filter to mitigate the effects of BDFT [5]. Other examples of mitigation studies are the works of Sövényi [6] and Sirouspour and Salcudean [7], who used a model-based cancellation approach. Recent work was presented in Ref. [8], where BDFT effects were mitigated in a backhoe (a type of excavator) by controlling cabin vibrations. These studies show not only a broad interest in the topic of mitigating BDFT, but also that there is a wide range of possible approaches to deal with the problem (see Ref. [3] for a review).

In the current paper, the effectiveness of a simple, cheap and widely-used hardware component is studied: the armrest.

Surprisingly, little is known about the effect of arm support on BDFT dynamics. Armrests can be found in a wide range of vehicles – from fighter jets to electric wheelchairs – and are often primarily employed to increase steering comfort and reduce fatigue. However, they are also effective in stabilizing the arm when subjected to motion disturbances [3]. Some studies suggested that an armrest may decrease the level of biodynamic feedthrough [1], [6], but often did not answer the questions '*how?*' and '*by how much?*'. An exception is a study by Torle [9], where the effect of an armrest was investigated by evaluating the tracking performance in an environment with random vertical accelerations with and without armrest. It was found that by providing an armrest, a greater improvement in tracking performance was achieved than by optimizing other control-stick parameters. However, the results also showed that the presence of an armrest did not remove all BDFT effects. Nevertheless, as an armrest is a cheap component that is easily designed and installed, it has the potential of being an excellent BDFT mitigation tool.

It is known that humans can and do vary the neuromuscular admittance of their limbs, e.g. their limb dynamics [10]. A human can, for example, depending on the task at hand, change his limb dynamics from being 'compliant' to being 'stiff'. Ref. [11] shows that BDFT dynamics change when the limb dynamics of the operator change. Ref. [12] shows that this variability of BDFT dynamics needs to take into account when trying to mitigate biodynamic feedthrough. Therefore, when investigating the effect of an armrest on the BDFT dynamics, the variability of the BDFT dynamics due to neuromuscular admittance needs to be taken into account. The approach of the current study is thus to determine the effectiveness of an armrest as a BDFT mitigation technique by measuring the BDFT dynamics with and without armrest for several subjects and three levels of the neuromuscular admittance, varying between 'compliant', 'relaxed', and 'stiff' dynamics.

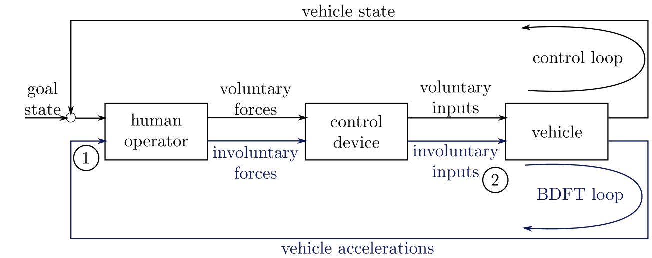

Fig. 1. Schematic representation of biodynamic feedthrough in a closed-loop vehicle control task

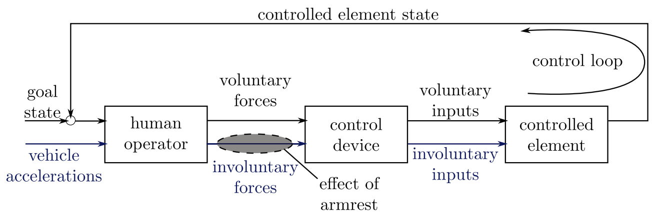

Fig. 2. Schematic representation of biodynamic feedthrough in an open-loop control task. The region where the armrest affects the feedthrough of accelerations is indicated

II. THE EFFECT OF AN ARMREST ON BDFT

A schematic representation of biodynamic feedthrough in closed-loop vehicle control is provided in Fig. 1. In the diagram a human operator is controlling a vehicle using a control device. The upper loop, the 'control loop', illustrates the observation of the vehicle state and comparison with a goal state by the operator. This results into voluntary forces applied to the control device, which yield voluntary control inputs to the vehicle. The lower loop, the 'BDFT loop', illustrates the feedthrough of vehicle accelerations through the body of the human operator, leading to *involuntary* forces and inputs. As these inputs yield new accelerations, that again can result in involuntary inputs, this type of system is called 'closed-loop BDFT system'.

In this study, the effects of an armrest on the BDFT dynamics, i.e., the dynamics between ① vehicle acceleration and ② involuntary control inputs are investigated (see Fig. 1). Therefore, it is possible to 'open the loop' and study the effect of an armrest by offering accelerations to a human operator, as opposed to having the operator controlling the accelerations directly. This situation is illustrated in Fig. 2. For experimental purposes, an open-loop BDFT system is preferred over the closed-loop type because it allows the experimenter to carefully design the acceleration signal [13]. The region where the armrest is expected to affect the BDFT dynamics is indicated in Fig. 2; by reducing the involuntary forces, the involuntary inputs are also reduced.

III. EXPERIMENT

An experiment was designed in which the BDFT dynamics were measured with and without armrest for different levels of neuromuscular admittance (i.e., different settings of the limb dynamics). In the following, this experiment will be described briefly; for more details the reader is referred to Ref. [14].

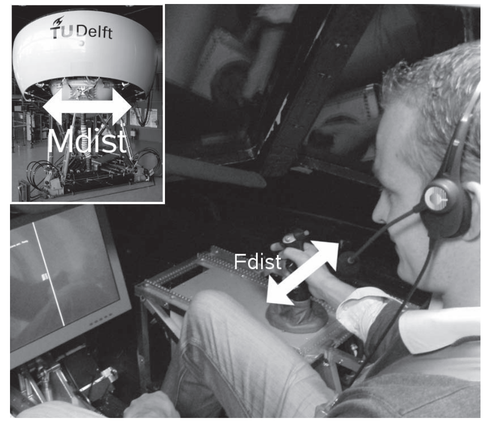

Fig. 3. Experimental setup used in this study: a subject uses the side-stick to perform a control task inside the simulator. F_{dist} perturbs the side-stick, M_{dist} perturbs the simulator.

A. Apparatus

The experiment was performed in the SIMONA Research Simulator (SRS) of TU Delft, a 6-DOF research flight simulator. The control device was an electrically actuated side-stick, located at the right-hand side of the subject. The measurements were performed with a side-stick because an armrest seems to be most practical for this type of control device. The armrest was a fixed (but removable) platform on which the subject could rest his arm (see Fig. 4). During the experiment, a motion disturbance M_{dist} was applied to the simulator's motion base – in order to measure the BDFT – and a force disturbance F_{dist} was applied to the side-stick – in order to measure the neuromuscular admittance – (see Fig. 3). In this study, only lateral (left-right) acceleration disturbances were studied. Also the neuromuscular admittance was only measured in lateral direction by using a lateral force disturbance on the control device. The control device was fixed in the longitudinal direction. Note that the measurement method can be easily extended to other directions in the future. A head-down display (15-in LCD, 1024x768 pixels, 60Hz refresh rate) was located in front of the subject. The seat had a five-point safety belt that was adjusted tightly in the experiments, to reduce torso motions.

B. Subjects

Fourteen subjects participated in the experiment without armrest and fourteen subjects participated in the experiment with armrest. Seven subjects participated in both experiments. In the current paper, only the data of these latter seven subjects will be analyzed. They were all male, right-handed and had a small variation in age (between 22 and 27 $years$) and body-mass-index (BMI) (between 18.1 and 24.5 kg/m^2). Details on the subjects can be found in Table I, listing the mean, standard deviation (SD) and range of subject parameters.

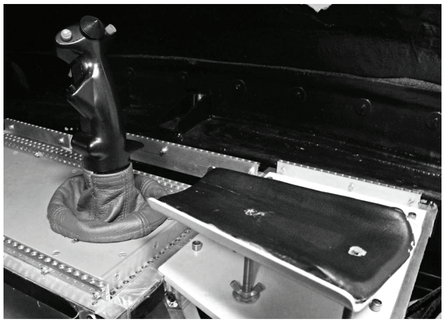

Fig. 4. The side-stick and armrest

TABLE I
DATA OF SUBJECTS (N=7, ALL MALE AND RIGHT-HANDED).

	Age ($years$)	Weight (kg)	Length (cm)	Fore arm (cm)	Upper arm (cm)	BMI (kg/m^2)
$mean$	25.0	73.7	185.0	28.9	35.3	21.6
SD	1.6	4.5	7.7	1.1	2.4	2.3
Range	22-27	68-82	175-194	28-30	28-30	18.1-24.5

C. Independent variables

Two independent variables were used: the control task (TASK) and the presence of an arm support in the form of an armrest (SUP). The different levels were:

1) TASK: Position task (PT); Force task (FT); and Relax task (RT)
2) SUP: armrest present (SUP); and armrest not present (NOSUP)

Together, TASK and SUP yielded six different conditions. Each of the conditions was repeated six times. For all subjects, the NOSUP condition was measured first, followed by the SUP condition. The order of the control tasks was randomized.

D. Task and task instruction

In the experiment, subjects performed three disturbance rejection tasks [10]:

- Position task (PT), in which the instruction is to keep the position of the side-stick in the centered position: resist the force perturbations;
- Force task (FT), in which the instruction is to minimize the force applied to the side-stick: yield to the force perturbations;
- Relax task (RT), in which the instruction is to relax the body and passively undergo the perturbations.

It is well known that human operators set their neuromuscular properties differently for optimal control of each of the three control tasks [10]. For the PT the best performance is achieved by being very stiff, the FT requires the operator to be very compliant. The RT yields an admittance reflecting the passive dynamics of the neuromuscular system. In earlier studies, identical tasks were used and it was shown that the BDFT dynamics strongly depend on these control tasks [11], [14].
Before entering the simulator, subjects were instructed on the goal of the experiment and the control tasks they were to perform. Several training runs were conducted to allow subjects to get used to the disturbances and the control tasks. During training, visual performance feedback was provided on the screen (visible in Fig. 3, see [14] for details) to help the subject understand the differences between the control tasks. After the execution of the task a score was provided (calculated using the standard deviation of control force and control position signal [14]). When a consistent performance (i.e., score) was reached, the visual performance feedback was removed from the screen for the remainder of the experiment – to minimize cognitive control actions based on visual feedback – and the actual measurement started. The measurements were performed first without armrest. In a second session, on a different day, the measurements with the armrest were performed.

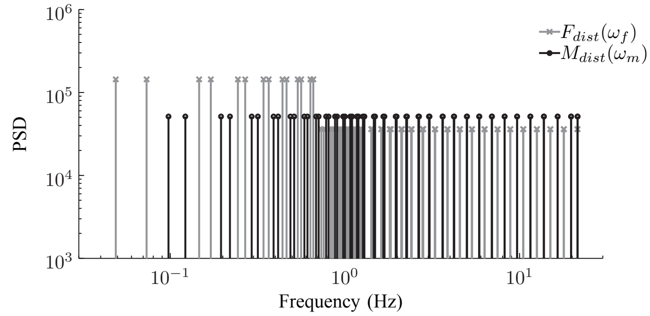

Fig. 5. Power spectral density plot of disturbance signals F_{dist} and M_{dist}.

E. Perturbation signal design

Both disturbance signals F_{dist} and M_{dist} were multi-sines, defined in the frequency domain. By separating the signals in frequency, see Fig. 5, the response due to each disturbance could be identified in the measured signals [10], [14]. To obtain a full bandwidth estimate of the admittance, a range of frequencies, ω_f, between 0.05 Hz and 21.5 Hz was selected for the force disturbance signal $F_{dist}(t)$. For the motion disturbance signal $M_{dist}(t)$, a range of frequencies, ω_m, between 0.1 and 21.5 Hz was selected.

F. Perturbation signal scaling

To minimize the effect of non-linearities and to be able to compare between different control tasks, the stick deflection in each task should be small and similar in size. In an effort to achieve this, the disturbance signals were scaled in a tuning procedure [14]. The goal of this procedure was to find, for each control task, the gains needed to result in similar standard deviation (3 degrees) of the control device deflection θ_{CD}. The tuning was done in the condition without armrest. The scaling factors for F_{dist} found for the PT, FT, and RT were 20, 1, and 0.38 respectively, resulting in signal root-mean-square (RMS) values of 10.17 N, 0.67 N, and 0.39 N. For the M_{dist} signal, the scaling factors (RMS in parentheses) for PT, FT, and RT were 0.9 (0.79 m/s^2), 0.7 (0.62 m/s^2), and 0.7 (0.62 m/s^2) respectively.

IV. Analysis

A. Calculating admittance and biodynamic feedthrough

The control device deflection, θ_{CD}, and the applied force to the control device, F_C, were averaged in the time domain over the six repetitions of a condition. The admittance was then estimated in the frequency domain, with a closed loop identification technique that used the estimated cross-spectral densities between $F_{dist}(t)$ and $\theta_{CD}(t)$ ($\hat{S}_{fd,\theta}(j\omega_f)$) and between $F_{dist}(t)$ and $F_C(t)$ ($\hat{S}_{fd,f}(j\omega_f)$) [15]:

$$\hat{H}_{adm}(j\omega_f) = \frac{\hat{S}_{fd,\theta}(j\omega_f)}{\hat{S}_{fd,f}(j\omega_f)}. \quad (1)$$

The estimate of the biodynamic feedthrough dynamics is calculated using the estimated cross-spectral density between $M_{dist}(t)$ and $\theta_{CD}(t)$ ($\hat{S}_{md,\theta}(j\omega_m)$) and the estimated auto-spectral density of $M_{dist}(t)$ ($\hat{S}_{md,md}(j\omega_m)$):

$$\hat{H}_{bdft}(j\omega_m) = \frac{\hat{S}_{md,\theta}(j\omega_m)}{\hat{S}_{md,md}(j\omega_m)}. \quad (2)$$

Note that the procedure to calculate $\hat{H}_{adm}$ and $\hat{H}_{bdft}$ assumes linearity. To check the extent to which this assumption holds the squared coherence was calculated (see [14]). After having calculated the results for each condition and for each subject, the results were again averaged, now in the frequency domain and across subjects, to obtain one admittance and BDFT estimate per condition. These are the results that will be analyzed in this study.

B. Comparing results with and without armrest

The biodynamic feedthrough estimate obtained with and without the armrest is denoted as $\hat{H}^{sup}_{bdft}(j\omega_m)$ and $\hat{H}^{nosup}_{bdft}(j\omega_m)$, respectively. For the admittance this is $\hat{H}^{sup}_{adm}(j\omega_f)$ and $\hat{H}^{nosup}_{adm}(j\omega_f)$. By comparing the dynamics obtained with and without the armrest, the influence of the armrest can be determined. An insightful way of visualizing differences is by looking at the ratio between the two dynamics. Ratio function $RF_{bdft}(j\omega_m)$ is defined as:

$$RF_{bdft}(j\omega_m) = \frac{\hat{H}^{sup}_{bdft}(j\omega_m)}{\hat{H}^{nosup}_{bdft}(j\omega_m)}, \quad (3)$$

such that:

$$\hat{H}^{sup}_{bdft}(j\omega_m) = RF_{bdft}(j\omega_m)\hat{H}^{nosup}_{bdft}(j\omega_m). \quad (4)$$

In this way, the ratio function describes the effect of the armrest on each frequency point. A value $RF = (1 + 0j)$, i.e., a magnitude $|RF| = 1$ and a phase $\angle RF = 0$, means that the dynamics with and without armrest are equal on that frequency. Other values indicate a difference in magnitude or phase or both. A similar ratio function can be calculated for the admittance estimate:

$$RF_{adm}(j\omega_f) = \frac{\hat{H}^{sup}_{adm}(j\omega_f)}{\hat{H}^{nosup}_{adm}(j\omega_f)}. \quad (5)$$

TABLE II
BDFT ratio function magnitude $|RF|$

freq (Hz)	FT	PT	RT	freq (Hz)	FT	PT	RT
0.11	0.37	0.41	0.30	2.26	0.49	0.35	0.49
0.21	0.39	0.50	0.24	2.65	0.65	0.37	0.60
0.31	0.40	0.51	0.26	3.04	0.79	0.33	0.79
0.40	0.44	0.41	0.30	3.63	1.04	0.28	1.28
0.50	0.52	0.47	0.28	4.21	1.49	0.25	2.18
0.60	0.53	0.37	0.27	4.99	3.50	0.26	2.61
0.70	0.57	0.38	0.28	5.87	2.55	0.33	1.61
0.79	0.49	0.44	0.28	6.95	1.48	1.32	1.33
0.89	0.49	0.41	0.30	8.22	1.02	1.24	1.32
0.99	0.62	0.38	0.30	9.68	1.05	1.12	1.11
1.09	0.57	0.38	0.30	11.54	0.92	1.06	1.01
1.18	0.56	0.44	0.34	13.78	1.07	1.25	1.10
1.28	0.48	0.42	0.33	16.52	0.91	1.20	0.95
1.48	0.43	0.40	0.35	19.74	1.19	1.14	0.71
1.67	0.37	0.38	0.39	21.50	0.70	1.15	1.01
1.97	0.40	0.38	0.41				

V. Results and discussion

Fig. 6 shows the magnitude and phase plot of the BDFT measured without armrest, with armrest and the ratio function. The thick lines indicate the means obtained by averaging over all subjects. The colored bands indicate the standard deviations (mean + 1 SD). Clearly, the BDFT dynamics measured without armrest show a dependency on the control task. At lower frequencies, the lowest BDFT occurs for the PT and the highest for the RT. Around approximately 2-3 Hz, the BDFT for the PT peaks and is higher than for other tasks. Similar results were found in other studies [3], [14].

The results obtained with the armrest also show a dependency of task, although the relationships have somewhat changed. It can be observed that, in general, the magnitude of the BDFT measured with an armrest is lower than without an armrest; this holds for all three tasks.

The ratio function allows for investigating the effect of the armrest in detail. Magnitude $|RF| = 1$ and a phase $\angle RF = 0$ are indicated by a thick black horizontal line. Solid horizontal grid lines are used to facilitate reading the ratio function's values. Table II lists the ratio function's magnitude values. From the results it can be concluded that the influence of the armrest on the BDFT dynamics depends on both control task *and* disturbance frequency. For lower frequencies, the presence of the armrest decreases the BDFT magnitude for all three tasks. Below frequencies of approximately 2 Hz, the ratio function is the lowest for the RT, signifying the largest decrease in BDFT magnitude. For this task, the ratio function's magnitude, $|RF|$, is around 0.3, meaning that the BDFT magnitude measured with armrest is reduced to 30% of the magnitude measured without armrest. For higher frequencies, it is the PT that shows the largest decrease in BDFT magnitude, showing an $|RF|$ between 0.3 and 0.4. For high frequencies, above 10 Hz, the ratio function is close to (1 + 0i), indicating no observable influence of an armrest on the BDFT dynamics at higher frequencies. Finally, an interesting feature can be observed around 5 Hz. At this frequency, peaks can be observed for each control task. Strikingly, the PT shows a peak in *reduction* in BDFT magnitude ($|RF| \approx$ 0.3) while the RT and FT show a

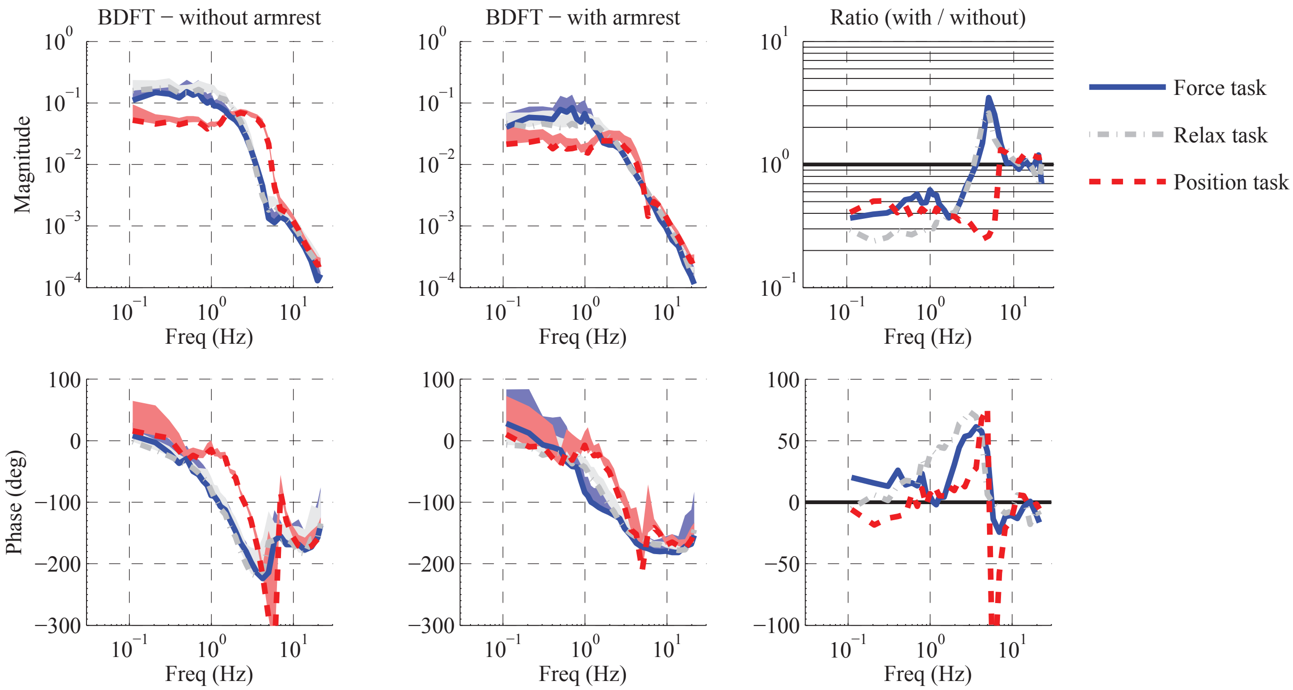

Fig. 6. The biodynamic feedthrough estimate, without armrest (left), with armrest (middle) and the ratio function (right). The lines show means, the colored bands show standard deviation (mean + SD shown).

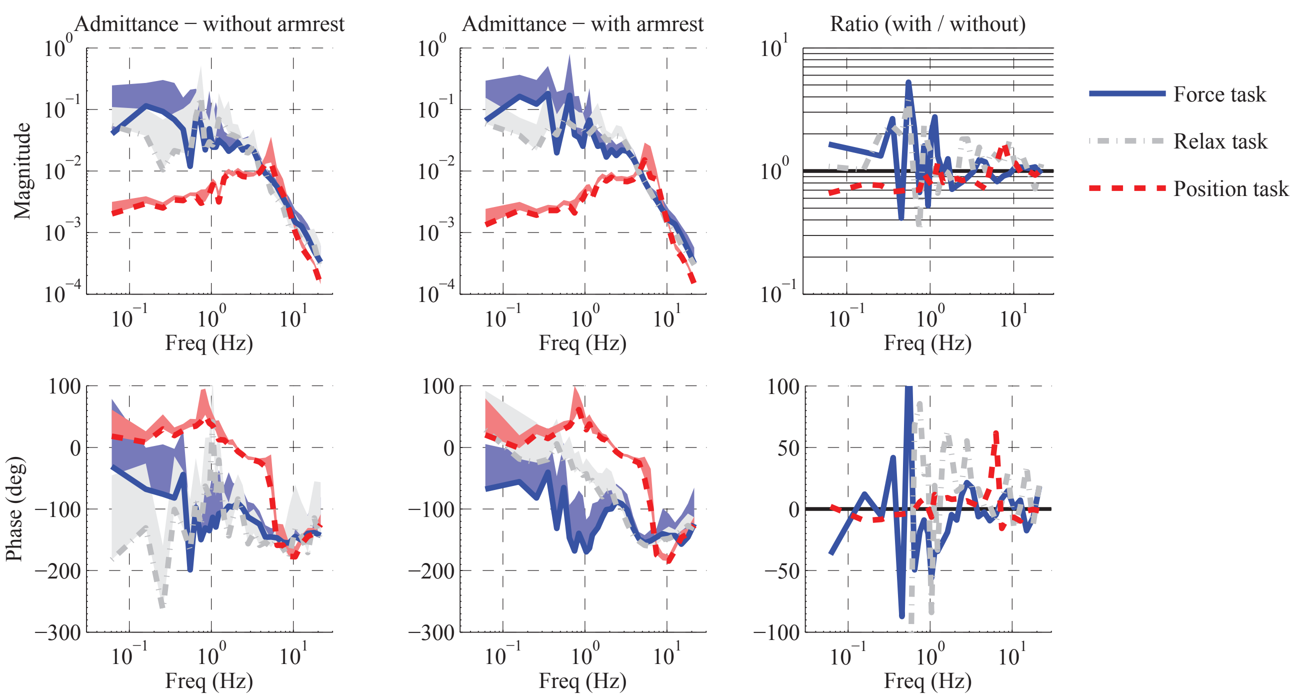

Fig. 7. The neuromuscular admittance estimate, without armrest (left), with armrest (middle) and the ratio function (right). The lines show means, the colored bands show standard deviation (mean + SD shown).

peak in *increase* in BDFT magnitude ($|RF| \approx$ 2-3). The cause of these peaks is yet to be investigated. It should be noted, however, that the BDFT magnitude around this frequency is relatively small, reducing the importance of this feature within the overall BDFT dynamics, at least in the open-loop case.

As BDFT dynamics strongly depend on the neuromuscular admittance, it is worthwhile to investigate the effect of the armrest on the neuromuscular admittance, as this might provide insight in the possible source of the differences in BDFT. Fig. 7 shows the magnitude and phase plot of the admittance measured simultaneously with the BDFT. The admittance measured without an armrest shows typical features [10], [14]: the lowest admittance is found for the PT; the highest for the FT; the admittance of the RT falls in between, as expected. Note that the phase of the RT shows some unusual behavior,with erratic phase changes ('jumps') and large standard deviations, especially below 1 Hz. These indicate that the estimate of the RT is not as accurate and reliable as desired, something that was observed in other studies as well [13], [14]. Here, however, the phase issue in the RT measurement are beyond the scope of the current paper. Except for the erratic phase behavior of the RT below 1 Hz, the admittance data measured with and without armrest shows to be similar. This is also reflected in the ratio function, which shows peaks but no structural increase or decrease in admittance. Only for the PT below 1 Hz a small but structural decrease in admittance can be observed ($|RF| \approx$ 0.7), meaning that the presence of the armrest allowed the subjects to express slightly stiffer behavior at lower frequencies. In general, it can be said that the admittance measured with and without armrest shows mainly unstructured differences, which leads to the conclusion that changes in admittance can be excluded as the cause of the observed changes in BDFT. In other words, the presence of an armrest does not change the limb dynamics of the human operator as such, but does change the feedthrough of involuntary forces to the control device, as indicated in Fig. 2.

VI. Conclusions

The effectiveness of an armrest in mitigating biodynamic feedthrough was investigated. The results show that, generally, the presence of an the armrest decreases the level of BDFT. This holds for each of the three levels of neuromuscular admittance investigated. However, the results also provide the novel insight that the effect of the armrest varies, both with frequency and neuromuscular admittance.

The results presented in this paper show that an armrest can be considered an effective tool in mitigating BDFT. The reduction obtained, especially at low frequencies, may very well be sufficient to obtain adequate task performance and prevent closed-loop oscillations in many practical situations which are currently suffering from the occurrence of BDFT. The fact that an armrest is cheap to produce and install might make this simple hardware component a serious competitor for advanced methods. In the current experiment, the study was performed for the lateral direction. The study can be easily extended to other motion directions. Also, it would be interesting to compare the mitigation effect of an armrest with other mitigation techniques, such as proposed in Refs. [6]–[8].

Acknowledgment

David Abbink is supported by VENI Grant 10650 from NWO. Prof. Heinrich H. Bülthoff is supported by WCU (World Class University) program funded by the Ministry of Education, Science and Technology through the National Research Foundation of Korea (R31-10008) and the myCopter project (European Commission 7th Framework Programme).

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