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A grip-force based scheduling of guidance forces

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Haptic guidance on demand: A grip-force based scheduling of guidance forces

Jan Smisek, Winfred Mugge, Jeroen B. J. Smeets, Marinus M. van Paassen, and André Schiele

Abstract—In haptic shared control systems (HSC), a fixed strength of guidance force equates to a fixed level of control authority, which can be insufficient for complex tasks. An adaptable control authority based on operator input can allow the HSC system to better assist the operator under varied conditions. In this paper, we experimentally investigate ($n = 8$) an adaptable authority HSC system that provides the operator with a direct way to adjust the control authority based on applied grip force. This system can serve as an intuitive 'manual override' function in case of HSC system malfunction. In a position tracking task, we explore two opposite approaches to adapt the control authority: increasing versus decreasing guidance strength with operator grip. These approaches were compared with unassisted control and two levels of fixed-level haptic guidance. Results show that the grip-adaptable approach allowed the operators to increase performance over unassisted control and over a weak guidance. At the same time, the approach substantially reduced the operator physical control effort required to cope with HSC system disturbances. Predictions based on the formalized model of the complete human-in-the-loop system corresponded to the experimental results, implying that such validated formalization can be used for model-based analysis and design of guidance systems.

Index Terms—System Design and Analysis, Dynamic Systems and Control, Human Performance

1 Introduction

HAPTIC SHARED CONTROL (HSC) systems combine manual control inputs of an operator with haptic guidance from an automatic system [1]. Generally it is implemented as a 'virtual spring', guiding the operator to follow a prescribed reference trajectory using additional forces on the control input device. The stiffness of this spring needs to match the task and the desired level of the HSC system authority over the task while still allowing the operator sufficient control [2]. Approaches to decide on the appropriate stiffness during the HSC system design vary in literature, from tuning the stiffness based on performance in iterated human-in-the-loop experiments [3], [4] to design procedures based on modeling and identification of the operator's limb neuromuscular properties [5], [6]. However, it has been recognized [7] that one fixed setting of the guidance stiffness is likely insufficient, especially in complex tasks, and a way to smoothly adapt the control authority during the task would be helpful.

With an adaptable HSC system, the operator would be able to rely on the guidance of the desired authority most of the time. Yet, when the task suddenly changes and becomes more difficult, or if an internal HSC system malfunction causes the guidance to be incorrect, the possibility to quickly change the level of authority and resolve the situation is of great practical importance [8]. If we consider an example of a lane keeping HSC system in a car, a change in the task difficulty could be caused by a wind gust pushing the car outside the lane or by the lane becoming more narrow [9]. In such a situation the driver would benefit from a higher level of haptic guidance support. On the other hand, the HSC system itself can be the source of the problem. For instance, the driver might have a different preference for the path to be taken than the HSC system, giving rise to a conflict. The driver would need to overrule the HSC system with increased effort and would, in such a situation, actually benefit from a lower level of guidance [10].

Traditionally, the research focus in the field of adaptive HSC systems was on approaches which decide the level of the HSC control authority *internally* (i.e., by the HSC system itself). Some of the previously presented approaches altered the control authority continuously to maintain high task performance [11] and safety [12], [13]. Other studies approach was to monitor the level of (dis-)agreement between guidance and operator, creating systems that gradually hand-over control to the operator based on increased interaction forces [14]–[18]. A conceptual combination of these approaches are 'assist-as-needed' systems that provide only the minimal guidance forces for sufficient task performance [19]–[21]. Further, other authors previously focused on actively recognizing the control model [22], [23] or on estimating the intended goal of the operator [24], [25]. Similar developments can be observed in 'policy-blending' guidance [26]–[28], where the system does not generate haptic guidance forces but rather the control input of the operator is directly altered (Ref. [29] provides a recent review).

We argue, that these previous approaches are making the final decision on *who is in control* – without involvement of the operators in the control loop – leaving them no direct way

- *J. Smisek is with the Telerobotics and Haptics lab, ESA (European Space Agency), Noordwijk, the Netherlands and with the Department of Control and Simulation, Faculty of Aerospace Engineering, Delft University of Technology, Delft, the Netherlands. E-mail: j.smisek@tudelft.nl*
- *W. Mugge is with the Department of Human Movement Sciences, Vrije Universiteit, Amsterdam, the Netherlands and with the Department of BioMechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, the Netherlands.*
- *J. B. J. Smeets is with the Department of Human Movement Sciences, Vrije Universiteit, Amsterdam, the Netherlands.*
- *M. M. van Paassen is with the Department of Control and Simulation, Faculty of Aerospace Engineering, Delft University of Technology, Delft, the Netherlands.*
- *A. Schiele is with the Telerobotics and Haptics lab, ESA (European Space Agency), Noordwijk, the Netherlands and with the Department of BioMechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, the Netherlands.*

to change the level of guidance support. However, we feel that the operators, while performing a task, do envision what level of control authority they would like to hold. We propose that this decision may be best left to them. To this end, we have presented a *grip-adaptable* HSC system [30], where the measured operator grip force was used as an additional input. The grip force provided the operator with a direct way to change the HSC system authority. We showed that such a system can reduce the physical workload of the operator as compared to HSC systems with fixed authority, while maintaining high tracking performance. Similar concept was later explored also by other authors [31], [32].

The goal of the current paper is to extend our previous study in two directions. First, we aim to extend and formalize the theoretical understanding of the conflicts and disturbances impeding a HSC system. Such formalized models can then be used, for example, in a model-based design workflow while designing complex HSC system in practice. Second, in addition to tracking performance and physical workload, other properties, such as the quantitative level of disagreement between the operator and the HSC system, are analyzed.

In Section 2, we first introduce a haptic shared control system with real-time adaptable authority and we put it on a firmer, system-theoretic basis, in Section 2.1. In Section 2.2, we formulate predictions based on the theoretical understanding of the HSC system on how the operators will react on the presence of conflicts and disturbances, and put them to the test in a human-in-the-loop experiment, in Sections 4 and 5. The paper concludes with a comprehensive discussion of the results and summary of the conclusions, in Sections 6 and 7.

2 HSC WITH GRIP-ADAPTABLE AUTHORITY

The underlying design goal of the presented grip-adaptable HSC is to make it intuitive. For this purpose, we try to take advantage of the natural adaptability of the human neuromuscular system: in general, humans adapt by stiffening up their limbs when keeping a fixed position is desired and by becoming more compliant when natural constraints of the environment seem adequate [33]. As stiffening up was found to be accompanied by increased grip force [34], one can capture these changes directly by measuring the force of the operator's grip on the master device handle. Based on this real-time grip force measurement, the stiffness of the HSC system (i.e., the level of control authority) is continuously adapted.

We aim to answer the following questions: 1) what are the reasons for the operator to increase the grip force during a task? 2) and how should the HSC system best adapt once this is detected? For the first question, based on the previous literature, there are two reasons for the increased grip force:

(a) *Task difficulty.* Increased grip force is a sign of an increased task difficulty and therefore the operator desires to be more supported by the HSC system [4], [12], [34]. In this paper, in order to increase task difficulty, sudden force disturbances, d_f in Fig. 1(a), were applied on the master device (effectively analogous to, e.g., wind pushing vehicle off the track). The operator needs to apply increased steering force to counteract the force disturbance and follow the center-line.

(b) *Conflict.* Increased grip force is a sign of conflict between the operator and the guidance and therefore the operator desires to have more control authority over the HSC system (i.e., less guidance support to reduce the influence of the conflicting HSC system) [11], [35]. Here, to replicate a conflict between the operator and the HSC, a step change in the HSC system reference trajectory was introduced (for example corresponding to the vehicle sensor picking-up a parallel track), illustrated as d_r in Fig. 1(b). The operator, in order to follow the center-line, needs to apply increased steering force to counteract the conflicting guidance force generated by the HSC system.

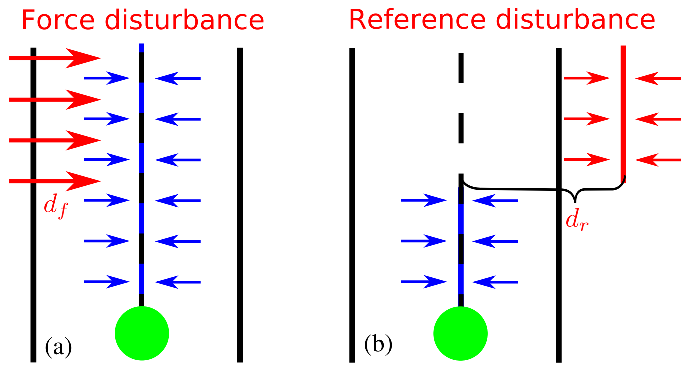


Fig. 1: Disturbances used in the experiment. The operator's task is to keep the green dot on the center-line of the track with the help of guidance forces (in blue). The force disturbance (a) increases the task difficulty by addition of a force d_f 'pushing' the dot outside the track. The reference disturbance (b) creates a conflict by guiding the operator to a trajectory outside the track offset by d_r. Correct guidance (in blue) and disturbances (in red) are not shown to the operators. Figure was adapted from [30].

As for the second question, these alternatives would lead to two competing control strategies: in (a) with increased grip force the level of guidance support (i.e., guidance stiffness) should be increased; and in (b) with the increased grip force the level of guidance support should be decreased.

In this paper we explore both control strategies separately and compare their effect on operator's performance and control effort. As a basis for comparison we use unassisted control and two levels of fixed guidance (with stiffness corresponding to the minimal and the maximal level of the adaptable-authority HSC system). We hypothesize, in Section 3, that each adaptable strategy would be more suitable for a specific type of disturbance, and that a stronger level of HSC authority would generally lead to a higher task performance (unless the HSC is in conflict with the operator).

2.1 Formalizing the grip adaptable HSC system

This section proposes a control-theoretic formulation that allows assumptions to be made about the effects of the aforementioned disturbances and the corresponding control HSC strategies. A grip-adaptable HSC system is illustrated in Fig. 2. The complete system comprises of an automatic *HSC system* part and a part representing a simplified model of an *Operator*. Both parts contribute to the task execution, namely in making the complete system output y follow the reference trajectory r (e.g., a road centerline detected by a sensor).

The complete system is modeled using transfer functions in Laplace domain, with a master input device (mass-damper):

$$G_m(s) = \frac{X_m(s)}{F_m(s)} = \frac{1}{m_m s^2 + b_m s}, \tag{1}$$

where X_m is the master device position, $F_m = F_h + F_{\text{guide}} + d_f$ is the sum of forces acting on it (uppercase is used to denote Laplace

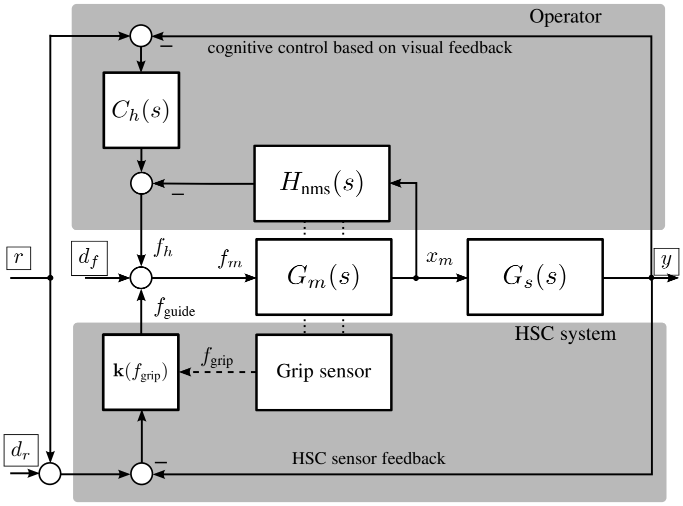


Fig. 2: Grip-adaptable HSC. Control scheme containing a simplified human operator model (visual controller C_h and neuromuscular system H_{nms}) that is supported by the HSC controller $\mathbf{k}(f_{\text{grip}})$ in making the output y of system C_s follow the reference trajectory r. Signals d_f and d_r are the respective force and reference disturbances.

domain variables). The master device has mass m_m and damping coefficient b_m. The master position, x_m, is tracked by a slave device position, x_s; the slave device is for simplicity modeled as a closed-loop system perfectly following x_m, as:

$$G_s(s) = \frac{Y(s)}{X_m(s)} \approx 1 \tag{2}$$

We model operators by making simplifying assumptions about their cognitive control and their neuromuscular dynamics (i.e., by using simple linear models with neglected delays). The cognitive control loop of the operator is considered to react on the visual feedback of the task, based on the control error $r - y$, with a simple proportional controller $C_h(s) = k_h$. The operator's neuromuscular system is modeled as a mass-spring-damper:

$$H_{\text{nms}}(s) = m_{\text{nms}}s^2 + b_{\text{nms}}s + k_{\text{nms}}, \tag{3}$$

with an assumed mass m_{nms}, damping coefficient b_{nms}, and stiffness k_{nms}. Finally, the grip adaptable haptic shared controller is introduced as a scalar function of the measured grip force $\mathbf{k}(f_{\text{grip}})$.

We describe the effects of two types of disturbance illustrated in Fig. 1. In the proposed systematic description, disturbances are introduced at two locations: a) a force disturbance d_f is added as an additional input command to the master device, representing the category of disturbances that directly affect the controlled master-slave system; b) a reference disturbance d_r is added to the reference trajectory r before it enters the haptic guidance controller, and as such, it only influences the HSC system (note that a similar effect would be achieved if the visual feedback of the operator would be manipulated). It should be also noted that, in practice, the disturbances acting on the complete system are in general not known and can be only observed by their effects.

The system outlined in Fig. 2 is analyzed below. The response $Y(s)$ to the reference trajectory $R(s)$, the force disturbance $D_f(s)$, and the reference disturbance $D_r(s)$, can be expressed as (Laplace 's' was left out for brevity):

$$\begin{aligned} Y = &\underbrace{\frac{G_m G_s\left(C_h + \mathbf{k}(f_{\text{grip}})\right)}{1 + G_m\left(H_{\text{nms}} + G_s\left(C_h + \mathbf{k}(f_{\text{grip}})\right)\right)}}_{\text{from reference trajectory}} R \\ &+ \underbrace{\frac{G_m G_s}{1 + G_m\left(H_{\text{nms}} + G_s\left(C_h + \mathbf{k}(f_{\text{grip}})\right)\right)}}_{\text{from force disturbance}} D_f \\ &+ \underbrace{\frac{G_m G_s \mathbf{k}(f_{\text{grip}})}{1 + G_m\left(H_{\text{nms}} + G_s\left(C_h + \mathbf{k}(f_{\text{grip}})\right)\right)}}_{\text{from reference disturbance}} D_r \end{aligned} \tag{4}$$

2.2 Steady-state system analysis

To provide insight into functionality of the HSC system and the effects of reference and force disturbances, Eq. (4) was combined with Eqs. (1,3), reformulated as a tracking error and evaluated for a steady-state $e_{\text{ss}} = r_{\text{ss}} - y_{\text{ss}}$, as:

$$e_{\text{ss}} = \frac{k_{\text{nms}}}{k_{\text{nms}} + k_h + \mathbf{k}(f_{\text{grip}})} r_{\text{ss}} \tag{5a}$$

$$+ \frac{1}{k_{\text{nms}} + k_h + \mathbf{k}(f_{\text{grip}})} d_{f_{\text{ss}}} \tag{5b}$$

$$+ \frac{\mathbf{k}(f_{\text{grip}})}{k_{\text{nms}} + k_h + \mathbf{k}(f_{\text{grip}})} d_{r_{\text{ss}}} \tag{5c}$$

The goal of the complete human-in-the-loop system is to minimize this tracking error, as: $e_{\text{ss}} \to 0$. The simplified system is influenced by three scalar gains: the operator's hand neuromuscular stiffness k_{nms}, the operator's visual control proportional gain k_h (neglecting any dynamics or internal delay), and finally the HSC system grip-force-adaptable gain $\mathbf{k}(f_{\text{grip}})$. We consider the three orthogonal inputs to the complete system, terms of an equation (5), and argue the desirable setting of the system gains for the following three cases:

(a) *No disturbance*. Based on the term (5a), the HSC system gains should: a) the HSC gain $\mathbf{k}(f_{\text{grip}}) \to \infty$ and the operator visual gain $k_h \to \infty$ (or as high as practical) to provide maximal tracking performance; b) and the operator needs to comply with the guidance force, $k_{\text{nms}} \to 0$.

(b) *Force disturbance*. The complete human-in-the-loop system (both the HSC system and the operator) should contribute in resisting the force disturbance. In line with term (5b), the HSC gain $\mathbf{k}(f_{\text{grip}})$, the operator's visual gain k_h, and the operator's stiffness k_{nms} should be as high as is practically achievable.

(c) *Reference disturbance*. According to term (5c), the HSC gain $\mathbf{k}(f_{\text{grip}}) \to 0$ and to compensate the remaining effects of d_r the operator visual gain k_h and the operator's stiffness k_{nms} should be as high as is practically achievable.

These analytic observations are next formulated into a set of hypotheses for the subsequent experiment.

3 HYPOTHESES

Two hypotheses were formulated for the experiment. First, as H_1, we hypothesize that, for the manual control and the fixed-gain controllers, a higher HSC gain will provide higher task performance in the undisturbed (*nominal*) and in the *force disturbance* case. In contrast, we hypothesize that a higher HSC gain would in the *reference disturbance* case lead to lower task performance.

The second hypothesis H_2 builds upon the steady-state analysis presented in the previous section. Here we look beyond task performance and focus on the suitability of the two proposed grip-adaptable HSC controllers (increasing versus decreasing guidance strength with operator grip) for the three disturbance cases (nominal, force, and reference). The H_2 is presented as three sub-hypotheses, which are summarized in Table 1. In this table, the hypothesized desirable settings (column 'Desired setting') of the operator's hand neuromuscular stiffness k_{nms} and of the HSC controller gain $\bar{\mathbf{k}}$ are based on the analysis discussed in Section 2.2. The decision which of the grip-adaptable controllers constitutes a more suitable HSC approach (column 'Suitable HSC?') can be illustrated using the following example. We consider $H_{2\text{a}}$: in a nominal task, the operator would try to take maximum advantage of the HSC and fully comply with the guidance, i.e., keeping the k_{nms} stiffness low. This would also correspond to a low grip force of the operator f_{grip} [34]. Based on the low f_{grip}, the two grip-adaptable strategies would behave very differently: the controller that *increases* guidance strength with operator grip would result in low $\mathbf{k}(f_{grip})$, which is not desirable (see Table 1, column 'Suitable HSC?' marked as a 'No'). Whereas using the controller that *decreases* guidance strength with operator grip would provide the desired high $\mathbf{k}(f_{\text{grip}})$ gain (marked as a 'Yes').

Following this line of reasoning, we hypothesize that for the human-in-the-loop experiment: $H_{2\text{a}}$) in a nominal task, the controller that *decreases* guidance strength with operator grip will constitute a more suitable HSC; $H_{2\text{b}}$) in presence of a force disturbance, the controller that *increases* guidance strength with operator grip will be more suitable; and finally $H_{2\text{c}}$) in presence of a reference disturbance, the controller that *decreases* guidance strength with operator grip will be more suitable.

TABLE 1: Hypothesized suitability of the proposed adaptable HSC controllers (sub-hypotheses of H_2).

Hypothesis	Disturbance	Desired setting		Suitable HSC?	
		k_{nms}	$\mathbf{k}(f_{grip})$	Increase	Decrease
$H_{2\text{a}}$	No (nominal)	Low	High	No	Yes
$H_{2\text{b}}$	Force	High	High	Yes	No
$H_{2\text{c}}$	Reference	High	Low	No	Yes

4 METHOD

4.1 Subjects

Eight subjects (one female), all employees of the European Space Agency, aged 28 to 41 years (with an average age of 32.6 years, $\sigma = 5.7$ years) participated in the experiment. All subjects had normal or corrected to normal vision. Seven subjects were right-handed and none reported recent injuries or any other disorder in the upper extremities. None of the subjects had any prior experience with haptic guidance. Subjects gave their informed consent prior to the experiment and no monetary compensation was offered.

4.2 Procedure and task instructions

The control input position $x_m(t)$ was visualized on a black screen with a green dot and the subjects were instructed to stay inside a prescribed moving sinusoidal track (marked with thick white borders) on the screen, Fig. 4, by actively moving the master device. During the experiment the subjects tracked a single sine reference trajectory, $r(t) = a\sin(2\pi f_r t)$, with amplitude of $a = 0.55$ rad (rotation required for the master device to follow the track), frequency of $f_r = 0.5$ Hz and the track half-width of $w_{\text{track}} = 0.055$ rad (10 % of the peak amplitude).

The complete experiment lasted approximately 90 minutes, including briefing, debriefing, practice runs, and breaks. Before the experiment, the subjects were provided with written instructions and were let to familiarize themselves with the hardware setup and the experimental procedure. Before every condition, the subjects were explained the functioning of the specific HSC (i.e., whether they can influence the HSC stiffness by changing the grip force), which type of disturbance would be applied in the trial, and then allowed to practice the exact condition for 60 sec. The experimental trial is described next.

4.3 Experimental trial

One experimental trial lasted exactly 130 seconds (65 periods of the 0.5 Hz reference signal), see Fig. 3. The first eight and the last two seconds of the measurement were removed from further analysis as run-in and run-out times. The 2 seconds of data immediately following a disturbance were also removed from the analysis.

For most of the trial, the subjects performed an undisturbed –nominal– task. In the nominal task, the reference trajectory was relatively easy to follow; however, the main source of unpredictability was provided by addition of disturbances. One type of disturbance was applied on eight occasions, for details see Section 4.5. This way, during each trial, measurements for both the nominal task and for one disturbance type were obtained. During the disturbance, the subjects were 'pushed' outside the track while their task was still to follow the visual reference track, i.e., they needed to actively resist the disturbances and stay on the track. The disturbances each lasted between two and four seconds, yielding between 16 and 32 seconds of disturbed signal per trial. The remaining part of the trial resulted in between 74 and 90 seconds of undisturbed (nominal) task. The time between disturbances was randomized to be between 7 and 15 seconds long.

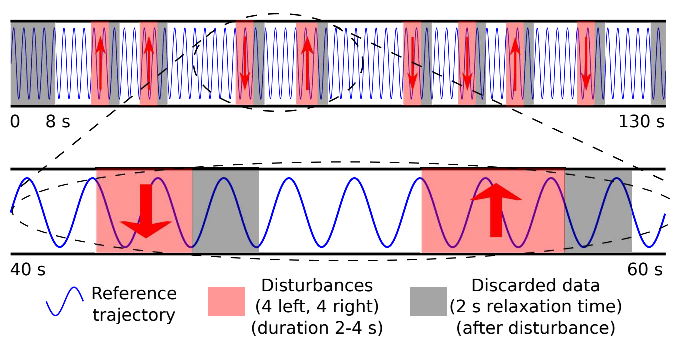


Fig. 3: Example of an experimental trial. During every trial disturbances were introduced at eight random occasions, yielding at least 16 seconds of measurement with disturbance and at least 74 seconds of undisturbed measurement.

4.4 Apparatus

The subjects were seated in an adjustable chair, such that the right forearm was parallel with the rotational axis of the joint, Fig. 4. The subjects sat approximately 80 cm from a 19-inch LCD screen and were presented with the green dot as the actual position $x_m(t)$, the white center-line and the thick white boundaries of the track. To provide additional visual cues on (un-)satisfactory performance, the controlled dot turned red whenever it moved outside the track boundaries.

The master position x_m was scaled to the horizontal position of the dot on the screen by 0.075 rad/cm, resulting in a side-to-side width of the track of approximately 16 cm. The track moved *downward* on the screen with a constant velocity, while the dot only moved sideways. At any time, the view contained 1.5 seconds of the future track and 2 seconds of the past track.

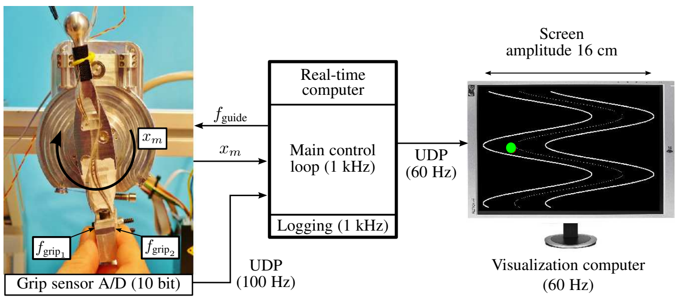


Fig. 4: Experimental setup. Input device (left) instrumented with grip force sensors was used to control the green dot on the screen (right) to stay inside the track (adapted from [30]).

The study was conducted on a 1-DOF experimental setup, Fig. 4, with one rotary joint additionally instrumented with foil force sensors to measure the operator's grip force. The control loop ran at a sampling frequency of 1 kHz. The unit composed of a brush-less DC motor, gearing stage (planetary gear and capstan) and an output handle. The motor was instrumented with an incremental encoder for velocity and position measurements.

The output shaft has a torque sensor that is used for the steering torque measurement. The handle of the device (with a length of $l_h = 70$ mm from the axis to the grip sensors) was equipped with a pair of foil force sensors (Tekscan FlexiForce A201 Sensors, with measuring range 0-110 N). The sensors were sampled at 100 Hz with a 10-bit A/D converter. The sensors were calibrated such that the effective linear range was between 0 and 15 N, with resolution of approximately 0.1 N. The reading from the sensors, $f_{\text{grip}_1}(t)$ and $f_{\text{grip}_2}(t)$, is low-pass filtered with a cut-off frequency of 10 Hz to suppress noise and use only data on frequencies the operator is able to generate.

However, in this configuration the measured forces not only contained the grip force but also a portion of the force used by the operator to move the control device. To get a real-time estimate of the grip force separately, only the reading from the sensor that is on the opposite side as is the direction of motion is used (i.e., only the sensor that is on the other side than the operator is pushing toward), as:

$$f_{\text{grip}}(t) = \begin{cases} f_{\text{grip}_1}(t), & \text{for } \dot{x}_m(t) \geq 0 \\ f_{\text{grip}_2}(t), & \text{for } \dot{x}_m(t) < 0 \end{cases} \tag{6}$$

4.5 Experiment design and Independent variables

The experiment used a within-subjects repeated-measures design consisting of two independent variables: 3 (types of disturbance: nominal task, the force disturbance, and the reference disturbance) x 5 (types of haptic shared controller: unassisted manual control, two levels of fixed-gain haptic assistance, and two grip-adaptable controllers). In total, each subject performed 10 trials during the experiment, as listed in Table 2. Every trial consisted of the nominal task part and of one type of (force – reference) disturbance, for details see Section 4.3. The order of the trials was balanced to minimize the effects of learning and fatigue on the experiment.

TABLE 2: Conditions completed by every subject

Disturbance	HSC controller									
	M		GW		GS		GA+		GA−	
Nominal	•[1]	•	•	•	•	•	•	•	•	•
Force	•		•		•		•		•	
Reference		∘[2]		•		•		•		•

[1] Each column represents a single experimental trial (the order was balanced between subjects).
[2] The reference disturbance only affects the HSC system, i.e., it has no effect on the unassisted manual control condition.

HSC controller implementation

The subjects were supported to stay on the center-line of the track $r(t)$ by applying a guidance force proportional to the deviation between the reference trajectory $r(t)$ and the green dot position $y(t)$ as:

$$f_{\text{guide}}(t) = \mathbf{k}(f_{\text{grip}}(t)) \, [r(t) - y(t)], \tag{7}$$

where $\mathbf{k}(f_{\text{grip}})$ is the guidance stiffness (for generality expressed as function of momentary grip force $f_{\text{grip}}(t)$). For the fixed-gain controllers two stiffness levels were used, specifically the weak and the strong guidance.

The weak guidance stiffness k_{GW} was selected such that the HSC system provides noticeable guidance force, but the operator is required to supply most of the control effort. In contrast, the HSC system with strong guidance stiffness k_{SG} setting was designed such that the HSC system itself can fully facilitate the nominal task (i.e., task without any disturbances).

The grip-adaptable controllers calculate their stiffness as proportional with the gain c_{GA} to the momentary measured grip force $f_{\text{grip}}(t)$ (obtained by Eq. (6)), with a positive sign for increasing guidance stiffness with operator grip force, and a negative sign for decreasing stiffness with operator grip. To allow the operator to comfortably hold the master device handle without affecting the HSC system stiffness gain, the grip force measurement is first subjected to a dead-band nonlinearity $\text{db}(x)$, so that the stiffness gain is not adapted until a minimal grip force threshold $f_{\text{grip}}^{\text{min}}$ is applied by the operator (the grip force is non-negative), as:

$$\text{db}(x) = \begin{cases} 0, & \text{for } x \leq f_{\text{grip}}^{\text{min}} \\ x - f_{\text{grip}}^{\text{min}}, & \text{otherwise.} \end{cases} \tag{8}$$

The calculated stiffness gain is limited between the stiffness gains of the fixed controllers (k_{WG} and k_{SG}), as:

$$\text{sat}(x) = \begin{cases} x, & \text{for } k_{\text{WG}} \leq x \leq k_{\text{SG}} \\ k_{\text{WG}}, & \text{for } x < k_{\text{GW}} \\ k_{\text{SG}}, & \text{for } x > k_{\text{GS}} \end{cases} \tag{9}$$

Finally, by including Eqs. (8) and (9), the complete grip-adaptable controller's stiffness functions are defined such that with increased grip force $f_{\text{grip}}(t)$ the stiffness is:

$$\begin{aligned} \text{increased:} \quad & \mathbf{k}\left(f_{\text{grip}}(t)\right) = \text{sat}\left\{k_{\text{GW}} + c_{\text{GA}}\,\text{db}\left[f_{\text{grip}}(t)\right]\right\}, \\ \text{decreased:} \quad & \mathbf{k}\left(f_{\text{grip}}(t)\right) = \text{sat}\left\{k_{\text{GS}} - c_{\text{GA}}\,\text{db}\left[f_{\text{grip}}(t)\right]\right\} \end{aligned}$$

For convenience, these stiffness functions are visualized in Fig. 5, for grip forces f_{grip} between 0 and 13 N. A summary of the guidance stiffness functions $\mathbf{k}(f_{\text{grip}})$, that were used as experimental conditions, is given in Table 3.

TABLE 3: List of HSC controller implementations

Color	HSC description	Code	HSC stiffness $\mathbf{k}\left(f_{\text{grip}}(t)\right)$
	Manual control	M	0
	Fixed, weak	GW	k_{WG}
	Fixed, strong	GS	k_{SG}
	Adaptable, increase with increased grip	GA+	$\text{sat}\left\{k_{\text{GW}} + c_{\text{GA}}\,\text{db}\left[f_{\text{grip}}(t)\right]\right\}$
	Adaptable, decrease with increased grip	GA−	$\text{sat}\left\{k_{\text{GS}} - c_{\text{GA}}\,\text{db}\left[f_{\text{grip}}(t)\right]\right\}$

* The controller gains were selected experimentally during a pilot experiment as: $k_{\text{GW}} = 0.5$ Nm/rad, $k_{\text{GS}} = 5$ Nm/rad, $c_{\text{GA}} = 0.5$, and $f_{\text{grip}}^{\min} = 1.75$ N .

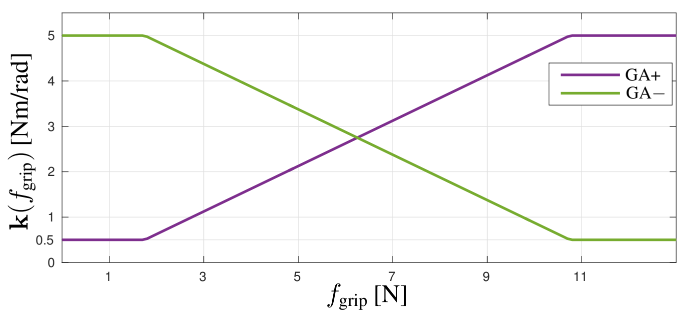


Fig. 5: Grip-adaptable controllers stiffness. HSC controller stiffness as function of the momentary grip force, saturated at the stiffness of the fixed controllers (k_{GW} and k_{GS}).

Disturbances

As illustrated in Fig. 1, the subjects were challenged in the task completion by two distinct types of disturbances:

(a) *Force disturbance.* The operators benefited during the whole task from correctly working guidance. On occasion, the task difficulty was increased by additional force ($d_f(t) = \pm 0.1$ [Nm]) applied by the master device. The operators then need to exert increased steering force to compensate for the disturbance (e.g., a wind gust).

(b) *Reference disturbance.* In the nominal situation, the visual task reference for the human operator and the haptic guidance reference are the same. However during some parts of the trial, a step disturbance is introduced to simulate a malfunction of the HSC system (e.g., the HSC picks-up a parallel lane). The operators are still supposed to follow the visually shown reference trajectory $r(t)$; however, the guidance disturbance ($d_r(t) = \pm 0.3$ [rad]) will essentially guide them to follow $r(t) + d_r(t)$, which they then need to compensate.

During every trial, a disturbance was introduced on 8 occasions (4 times to the left and 4 times to the right). The direction (left-right), time between disturbances and their duration were randomized to prevent anticipation.

4.6 Dependent measures

The dependent measures used to compare the studied conditions can be divided into three categories: task performance, operator workload, and HSC effectiveness. The dependent measures are listed in Table 4.

TABLE 4: Experiment dependent measures.

Measure	Symbol	Description
Performance	$\bar{e}_{\text{off}}$	Mean off-track excursion [rad]
Operator control effort	$\bar{f}_h$	Mean steering force [N]
	$\bar{f}_{\text{grip}}$	Mean grip force [N]
HSC effectiveness	$\overline{D}$	Mean guidance disagreement [/]
	$\bar{\mathbf{k}}$	Mean HSC stiffness [Nm/rad]

The dependent measures were calculated for every trial, at discrete times n (with a time step of 1 ms). All metrics were averaged separately for the disturbance conditions (nominal and disturbed). In other words, the time step $n \in [1 \dots N]$ signifies that based on the specific disturbance conditions, the metrics were averaged only over the corresponding parts of the trial.

Mean off-track excursion

To assess how well the subjects managed to stay within the bounds of the prescribed trajectory (of half-width w_{track}), a mean off-track excursion was calculated as: $\bar{e}_{\text{off}} = \frac{1}{N}\sum_{n=1}^{N} e(n)$, where

$$e(n) = \begin{cases} |r(n) - y(n)| - w_{\text{track}}, & \text{for } |r(n) - y(n)| > w_{\text{track}} \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

Mean steering force

The physical workload of the operator was calculated as the mean magnitude of the interaction force between the operator and the master device, recorded by the torque sensor in the handle output shaft, $\bar{f}_{\text{h}} = \frac{1}{l_h}\frac{1}{N}\sum_{n=1}^{N}\left|\tau_{\text{sensor}(n)}\right|$, where the handle length $l_h = 0.07$ m was used to scale the torques to forces at the contact point where the operators held the handle, see Fig. 4.

Mean grip force

The mean magnitude of the grip force was calculated both as a means to study the different adaptable controllers and to assess the physical workload associated with maintaining increased grip force. The metric was calculated from a mean of the grip force sensor measurements, pre-processed according to Eq. (6), as $\bar{f}_{\text{grip}} = \frac{1}{N}\sum_{n=1}^{N}|f_{\text{grip}}(n)|$.

Mean guidance disagreement

The possible disagreement between the operator and the HSC system was evaluated using the haptic guidance disagreement metric [11]. The metric is based on calculating the internal forces $f_i(n)$, that occur if the forces generated by the operator, $f_h(n)$, and force by the HSC, $f_{\text{guide}}(n)$, are in opposite directions (the time-step n was omitted for brevity):

$$f_i = \begin{cases} f_h, & \text{if } \operatorname{sign}(f_h) \neq \operatorname{sign}(f_{\text{guide}}) \wedge |f_h| \leq |f_{\text{guide}}| \\ f_{\text{guide}}, & \text{if } \operatorname{sign}(f_h) \neq \operatorname{sign}(f_{\text{guide}}) \wedge |f_h| > |f_{\text{guide}}| \\ 0, & \text{if } \operatorname{sign}(f_h) = \operatorname{sign}(f_{\text{guide}}) \end{cases} \tag{11}$$

The disagreement is then calculated as the mean internal force $\bar{D} = \frac{1}{N}\sum_{n=1}^{N} |f_i(n)|$.

Mean HSC stiffness

The mean HSC system stiffness was calculated to study how the operators were able to use the two different adaptable controllers, as: $\bar{\mathbf{k}} = \frac{1}{N}\sum_{n=1}^{N} \mathbf{k}\left(f_{\text{grip}}(n)\right)$.

4.7 Data analysis and visualization

To investigate H_1 and to provide general comparison of the studied HSC approaches, the statistical analysis of the experimental results was first conducted using a two-way repeated measures ANOVA, with significance level of $\alpha < 0.05$. The sub-hypotheses of H_2 were assessed using a paired t-test. The ANOVA results were further evaluated with post-hoc multiple comparison Tukey HSD tests. Normality of the data was verified using the Lilliefors' test at the 5% significance level. The assumption of sphericity was assessed using Mauchly's test; for non-spherical data the Greenhouse-Geisser corrections were applied to the degrees of freedom [36]. In the pair-wise comparisons, the absolute effect sizes are reported for measures with intrinsic meaning (e.g., the difference of mean steering forces).

The results are presented separately for the 'Nominal' and both 'Disturbed' parts of the task. Mean results of subjects are color-coded and keep the left-to-right position between figures to allow assessment of their individual performance. Median, 25th and 75th percentiles and the maximal and minimal values for all subjects are shown in the following figures. Statistic significance is visualized in the plots below with the following notation marking the significance levels: • for $p \leq 0.05$, •• for $p \leq 0.01$, and ••• for $p \leq 0.001$. The HSC controller conditions are colored according to Table 3. Since there was no guidance provided in M, its results are excluded in the reference disturbance conditions and also in all conditions for the mean guidance disagreement metric.

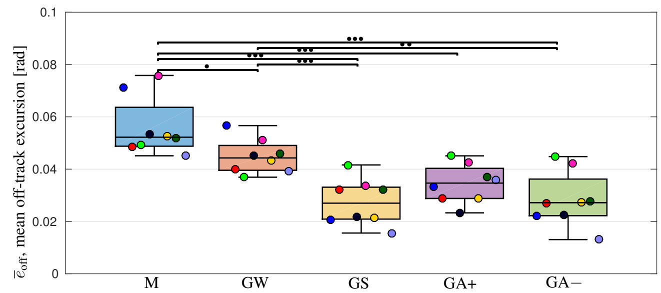
5 Results

In this section, statistically significant results relevant to the hypotheses (based on the post-hoc multiple comparisons) are reported together with appropriate effect sizes.

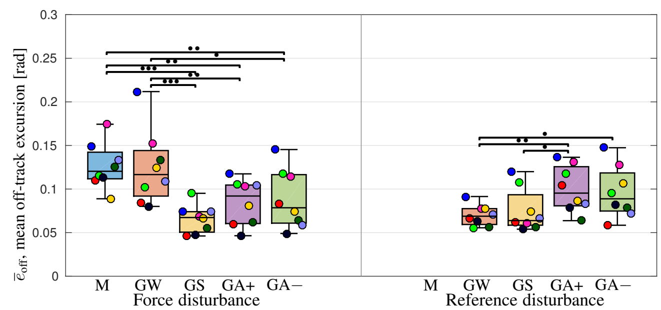
The *nominal* results were combined from both the Force and Reference disturbance trials; paired t-tests were performed to confirm that there are no significant differences between those ($p > 0.05$ for all HSC controllers and metrics). In Figures 6 to 9, the *nominal* part of the trials, in (a), is evaluated separately from both *disturbed* parts, in (b).

5.1 Task performance: mean off-track excursion

To investigate hypothesis H_1, that relates task performance to HSC controller stiffness, the mean off-track excursion was compared in Fig. 6. There was an effect of both the type of HSC ($F_{0.67,4.71} = 6.3,\ p = .004$) and disturbance ($F_{0.34,2.36} = 23.0,\ p < .001$) on the task performance. In the nominal part of the trial, Fig. 6a, all haptic shared controllers provided higher performance over the manual control condition M ($p < 0.05$). Notably, the GA− performed better than the fixed weak controller GW ($p < 0.01$). In the disturbed part of the trial, Fig. 6b, when the force disturbance was applied, the fixed strong controller GS, and both adaptable controllers GA+ and GA− performed better than the manual control condition M and the fixed weak controller GW ($p < 0.01$). For the reference disturbance, both adaptable HSCs GA+ and GA− performed worse than the GW ($p < 0.05$).



(a) Nominal



(b) Disturbed

Fig. 6: Mean off-track excursion showing the effect of disturbances on the tested HSC controllers, with higher values denoting lower task performance. Stronger guidance in general provided higher task performance. Note that the y-axes are different.

5.2 Operator control effort: steering force

The mean absolute steering force was compared in Fig. 7. The type of HSC ($F_{0.67,4.72} = 10.5,\ p = .001$) and disturbance ($F_{0.34,2.36} = 14.7,\ p < .001$) had an effect on the steering force.

During the force disturbance, Fig. 7b, the GS, and both adaptable controllers GA+ and GA− required the operator to apply lower mean steering force than the manual control condition M and the fixed weak controller GW ($\Delta\overline{f}_h = 1.42\,\text{N},\ \text{CI}_{95\%}\ [0.78, 2.06],\ p < 0.001$). In the reference disturbance case, the strong fixed guidance GS required the operator to apply the highest steering force among the controllers (compared to GA−: $\Delta\overline{f}_h = 4.79\,\text{N},\ \text{CI}_{95\%}\ [3.55, 6.03],\ p < 0.001$). Amongst the adaptable controllers, the GA+ required higher steering force than GA− ($\Delta\overline{f}_h = 1.77\,\text{N},\ \text{CI}_{95\%}\ [0.28, 3.26],\ p = 0.022$.

5.3 Operator control effort: grip force

In Fig. 8, mean grip force was compared; the type of HSC ($F_{0.77,5.36} = 7.9,\ p = .005$) and disturbance ($F_{0.38,2.68} = 8.9,\ p = .005$) both had an effect on the grip force. In the nominal part of the trial, Fig. 8a, the adaptable controller GA+ resulted

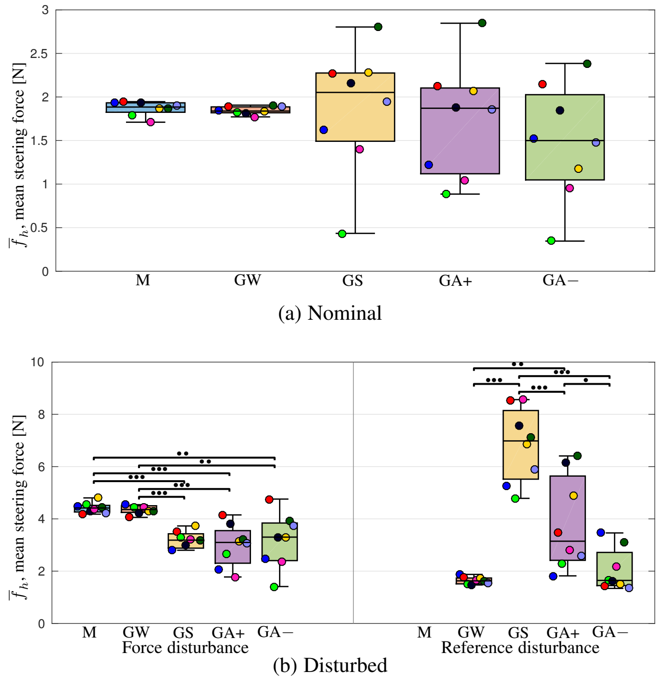


Fig. 7: Mean steering force showing the effect of disturbances on the tested HSC controllers. Both adaptable controllers allowed to reduce the steering force (compared to GS) necessary to compensate effect of the reference disturbance. Note that the y-axis are substantially different.

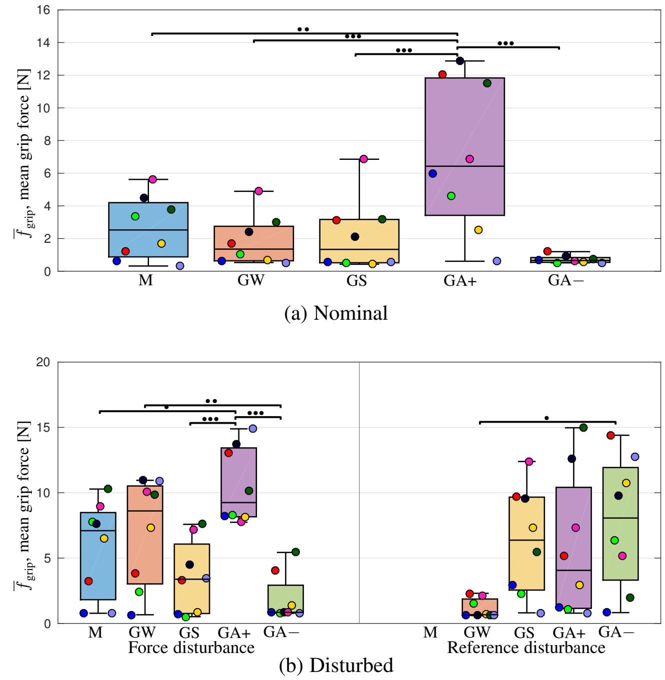


Fig. 8: Mean grip force showing the effect of disturbances on the tested HSC controllers. The GA+, in accordance with its design, requires higher grip force.

in highest mean grip force among the controllers (compared to GA−: $\Delta\overline{f}_{\text{grip}} = 5.06\,\text{N},\ \text{CI}_{95\%}\ [2.69, 7.44],\ p < 0.001$). When the force disturbance was present, Fig. 8b, the GA+ still required higher $\overline{f}_{grip}$ than all other controllers beside GW (compared to GA−: $\Delta\overline{f}_{\text{grip}} = 7.69\,\text{N},\ \text{CI}_{95\%}\ [4.94, 10.45],\ p < 0.001$). The adaptable controller GA− resulted in lower mean grip force than GW ($\Delta\overline{f}_{\text{grip}} = 4.41\,\text{N},\ \text{CI}_{95\%}\ [1.57, 7.25],\ p = 0.004$). When the reference was disturbed, the fixed weak controller GW resulted in a lower mean grip force compared to GA− ($\Delta\overline{f}_{\text{grip}} = 6.04\,\text{N},\ \text{CI}_{95\%}\ [2.23, 9.86],\ p = 0.004$).

5.4 HSC effectiveness: haptic guidance disagreement

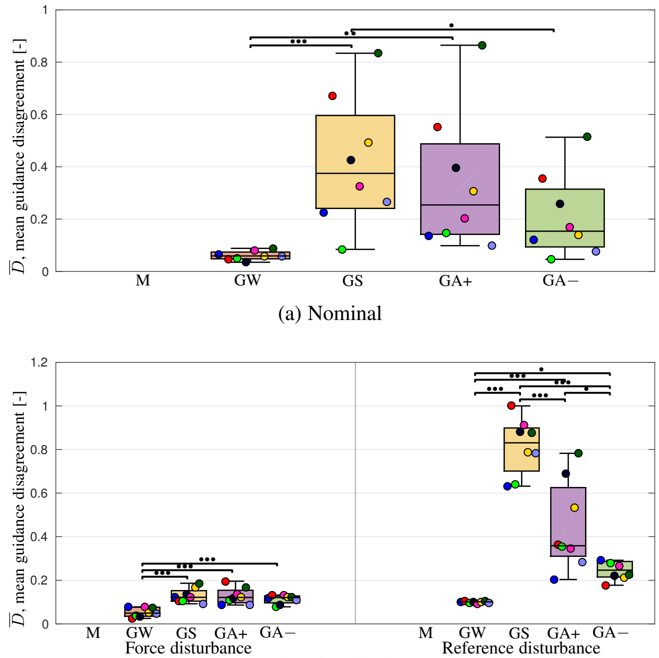
Mean haptic guidance disagreement results are shown in Fig. 9. Both the type of HSC ($F_{0.48,3.36} = 59.6,\ p < .001$) and disturbance ($F_{0.24,1.68} = 113.3,\ p < .001$) had an effect on the haptic guidance disagreement. In the nominal part of the trial, Fig. 9a, the GW and GA− were the least opposed by the subjects, i.e., resulted in the lowest disagreement ($p < 0.05$). When the force disturbance was present, Fig. 9b, the GW still resulted in the lowest disagreement among the controllers ($p < 0.001$). When the reference was disturbed, the fixed weak controller GW resulted in lowest disagreement ($p < 0.05$), the adaptable GA− scored second ($p < 0.05$), with lower $\overline{D}$ than GA+ ($p < 0.05$). Finally, the fixed strong controller GS exhibited the highest level of disagreement ($p < 0.001$). It should be noted that the low haptic guidance disagreement values for the GW controller are not surprising and are due to the low stiffness of the HSC.

5.5 HSC effectiveness: mean HSC stiffness

To investigate the predicted usage of both adaptable controllers (hypothesis H_2), mean haptic guidance stiffness gains $\overline{\mathbf{k}}$ are analyzed in Fig. 10. The type of HSC ($F_{0.41,2.84} = 131.8,\ p < .001$) and disturbance ($F_{0.20,1.42} = 193.4,\ p < .001$) both had an effect on the haptic guidance disagreement. In the nominal case (sub-hypothesis $H_{2\text{a}}$), for both force and reference disturbance trials, a paired t-test did not reveal a statistically significant difference between the GA+ and GA− controllers ($t_7 = -0.51,\ p = 0.63$). With both controllers, the operators on average maintained equally high $\overline{\mathbf{k}}$ gain settings.

The absolute effect sizes were calculated to evaluate the effect of the applied disturbance on $\overline{\mathbf{k}}$. Comparing the nominal task in contrast to the force disturbance case, addressed by sub-hypothesis $H_{2\text{b}}$, while using the GA+ controller, the operators maintained the level of $\overline{\mathbf{k}}$ between the Nominal task and Force disturbance situations ($\Delta\overline{\mathbf{k}} = 0.62\,\text{Nm/rad},\ \text{CI}_{95\%}\ [-0.21, 1.45],\ p = 0.121$). In trials when the GA− controller was used, the HSC gain decreased in reaction to the disturbance ($\Delta\overline{\mathbf{k}} = -0.97\,\text{Nm/rad},\ \text{CI}_{95\%}\ [-1.14, -0.79],\ p < 0.001$). The operators on average managed to maintain high $\overline{\mathbf{k}}$ gain setting with the GA+ controller. In contrast, the average $\overline{\mathbf{k}}$ gain even decreased with the GA− condition.

Comparison of the nominal task to the reference disturbance case, addressed by sub-hypothesis $H_{2\text{c}}$, there was no adaptation of the $\overline{\mathbf{k}}$ between the Nominal task and Reference disturbed situations with the GA+ controller ($\Delta\overline{\mathbf{k}} = -0.37\,\text{Nm/rad},\ \text{CI}_{95\%}\ [-1.00, 0.26],\ p = 0.210$). When the GA− controller was used, the HSC gain decreased in reaction to the reference disturbance ($\Delta\overline{\mathbf{k}} = -2.02\,\text{Nm/rad},\ \text{CI}_{95\%}\ [-2.58, -1.46],\ p < 0.001$). Using the GA− controller, the operators were able to decrease the $\overline{\mathbf{k}}$ gain setting, when they were in conflict with the HSC system (reference disturbance). However, there was no decrease of the $\overline{\mathbf{k}}$ when the GA+ was used.



(a) Nominal

(b) Disturbed

Fig. 9: Mean haptic guidance disagreement showing the effect of disturbances on the tested HSC controllers; higher values denote lower agreement between the operator and the HSC system. The GS exhibited highest disagreement.

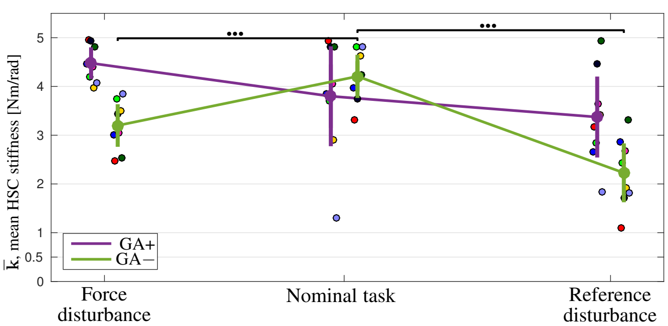


Fig. 10: Subject means (open symbols) and mean over all subjects (filled symbols $\pm$ 95% CI) of the mean HSC stiffness showing change in reaction on disturbance. During the force disturbance, the operators were able to maintain HSC stiffness with the GA+ controller. When the reference was disturbed, the GA− controller allowed the operators to reduce the HSC stiffness. Note that the HSC stiffness range was set to $0.5 - 5$ Nm/rad.

6 Discussion

This study provides a formalized and validated operator adaptable haptic shared control (HSC) system. We studied how the operator can take advantage of this system in three situations: 1) we studied how operators can use the HSC system in a nominal (undisturbed) task; 2) moreover, we investigate how the operators can cope with the effects of the force disturbances (that increased the task difficulty but the HSC system was still acting on the same control goal as the operator); 3) and how they cope with the presence of a reference disturbance (which represented a conflict between the goals of the operator and the HSC system). The following sub-sections discuss the observed effects.

6.1 Stronger guidance improves performance but promotes disagreement

In accordance with the hypothesis H_1, stronger HSC stiffness resulted in higher performance, with comparable steering force for all controllers, in the nominal task. However, the fixed strong GS controller was opposed by the operators (i.e., exhibited a high HSC disagreement $\overline{D}$). This can be attributed to the operators having a different preference on how the reference trajectory should be followed (e.g., by 'cutting curves' as observed in [2]). A promising approach to alleviate this issue might be to adjust the HSC system reference trajectory (within task limits) to more closely match an operator-preferred trajectory [37]. Contrary to hypothesis H_1, no difference in performance was found between M and GW controllers during the force disturbance condition.

Furthermore, also contradicting what was hypothesized in H_1, when the reference was disturbed, the operators still managed to achieve high task performance, even with the strong fixed HSC controller (which presented the highest erroneous guidance force). The operators compensated for this by exerting substantially higher steering force $\overline{f_h}$, which would be exhausting over a prolonged period of time.

6.2 A control-theoretic model can predict the behavior of the adaptable HSC controllers under disturbances

We performed and analyzed an experiment in which operators had to perform a task under the influence of the above mentioned disturbances. The experimental results comparing suitability of the two proposed grip-adaptable HSC controllers match the predictions based on the control-theoretic model (formulated as hypothesis H_2).

Following the analysis presented in Section 2.1, we hypothesized (for summary of sub-hypotheses of H_2 see Table 1), that in the nominal situation it is desirable to provide high HSC system gain $\overline{\mathbf{k}}$ while the operator remains compliant with the haptic guidance forces. We predicted that the more suitable controller would be the GA−. Based on the experimental results, Fig. 10, both adaptable controllers exhibited comparably high $\overline{\mathbf{k}}$ in the nominal condition. The GA− controller allowed to achieve that with substantially lower HSC disagreement $\overline{D}$, i.e., the operators tended to comply more with the guidance. This finding is in agreement with the sub-hypothesis $H_{2\mathrm{a}}$.

In case of the force disturbance, the GA+ was predicted to be the more suitable controller. In accordance with this expectation, the GA+ allowed the operators to maintain the high $\overline{\mathbf{k}}$, whereas the GA− controller was accompanied with a decreased $\overline{\mathbf{k}}$. This observation agrees with the assumption that high operator neuromuscular system stiffness corresponds to high grip force. When the force disturbance is present and the operators have to resist it (by stiffening up), the accompanied increased grip force causes an unwanted decrease in the GA− controller gain (and a desirable increase with GA+), supporting sub-hypothesis $H_{2\mathrm{b}}$.

For the reference disturbance, the GA− was expected to be the better controller. In agreement with the prediction, the operators were able to correctly utilize the GA− and decrease $\overline{\mathbf{k}}$, effectively lowering the negative influence of the disturbed guidance and substantially minimizing the necessary steering force $\overline{f_h}$ to overcome it. In contrast, there was no measurable reduction while using the GA+ controller gain $\overline{\mathbf{k}}$, supporting sub-hypothesis $H_{2\mathrm{c}}$, and the operators had to use higher $\overline{f_h}$ to compensate for it.

We conclude that the average reaction of the operators match our control-theoretic predictions and it is thus possible to formalize the effects of aforementioned disturbance in HSC systems. In the future, such validated formalization can be used for model-based analysis and design of HSC systems in the presence of disturbances. The system formalization presented in 2.1 is relatively general and would already allow modeling various use cases, such as teleoperation or car steering. However, to provide recommendations on the most appropriate HSC policies for other real-life systems, the presented formalization might need to be extended with other potential disturbance sources.

6.3 Adaptable guidance with reduced steering force leads to increased performance

Results of both adaptable controllers, GA+ and GA−, in the nominal and force disturbance parts of the task, show that the operators were able to perform the task better than with the fixed weak guidance GW. In other words, the operators were able to take advantage of the flexibility provided by the adaptable guidance approach and increase their task performance by opting for higher guidance stiffness setting, up to the level of strong fixed guidance GS. Moreover, the operators were able to use the adaptable controllers GA+ and GA− to minimize the necessary steering they had to apply, to the level of GS.

However, the GA+ controller was associated with overall higher grip force and HSC disagreement, adding to the operator's physical effort. This might prove impractical for an HSC system that would be used over extended periods of time. Such system can be designed to, for example, react to the relative changes of the grip force, as opposed to the absolute grip force value that was used in this study.

6.4 Relevance to other applications

The proposed approach essentially adds a more direct control over the HSC system – without negatively affecting the performance. We observed that the operators did not significantly change their grip during the task with fixed-authority HSC systems whereas they took advantage of the authority adaptation if provided with the option. For instance, the described HSC system can: a) serve as a fast and intuitive 'manual-override' function in case of malfunctioning automation when the operator needs to quickly take over [8], [13], possibly limiting negative effects of inaccuracies in HSC systems [38], [39]; b) it could be useful in more complex tasks where easier departures from original goals might be a desirable property, for example in lane changing with car driving HSC systems [40] or to allow switching between several sub-goals in teleoperated assembly tasks [24], [41]; c) the approach could be suitable for training of manual skills using haptic guidance. It was shown that progressively decreasing level of guidance force better facilitates learning and retention of tasks [42]–[44]. From this point of view, the training would be at the beginning facilitated by strong guidance force, that could then diminish as the operator gets more confident and assumes more authority over the task.

6.5 Applicability beyond a single degree-of-freedom

The presented approach uses a single degree-of-freedom (DOF) grip force measurement as an input to adapt an HSC system also operating in a single DOF task. However, in a multi-DOF system, the grip force measurement could be directly used to adapt the guidance stiffness of the HSC system (i.e., using the same principle to scale the HSC stiffness uniformly in all DOFs). Some practical tasks might require adapting the HSC stiffness differently in different DOFs; an example is a 6-DOF teleoperated peg-in-hole insertion task. An HSC system for this type of tasks is often implemented such that it provides the guidance to the teleoperators to minimize the lateral misalignments but leaves them free to move unguided in the direction of the hole axis [45]. The grip force input could be then used to adapt the HSC stiffness only in the lateral direction.

6.6 Limitations

The experimental conditions only exposed the operator to either increased task difficulty (force disturbances) or conflicting goals of the guidance (reference disturbances). The operators were fully aware of which type of disturbances to expect and could learn how to respond. Furthermore, the followed reference trajectory was very regular (sine wave). In a practical, real-life application, both types of disturbances could occur, and the reference trajectory might not be easy to anticipate. How well the operators would be able to distinguish those and perform in such situations remains for further investigation.

Further, the number of participants in this study was relatively low, which constrains how representative our findings may be for the general population.

7 Conclusions

This paper provides an experimentally verified formalization of a haptic shared control system operating in the presence of goal-related conflicts and task-difficulty-altering disturbances. To cope with these additional realistic challenges, a new approach for adapting the authority of the guidance based on the operator's grip force was presented. For the studied experimental conditions we conclude that: 1) the proposed formalization provides a viable method to analyze goal-related conflicts of HSC systems; 2) with the proposed adaptable-authority haptic shared controller the operator achieved increased performance over the weak (possibly 'under-tuned') fixed guidance, up to the level comparable with the strong fixed guidance setting; 3) thanks to the adaptable-authority 'decreasing guidance authority with increased grip' controller, the steering force necessary to overcome the incorrect guidance was significantly reduced over the fixed-authority HSC with strong tunning (while maintaining comparable performance); 4) the adaptable-authority controller also exhibited a reduced disagreement between the operator and the guidance, suggesting that the subjects were able to successfully adapt the HSC setting closer to their preference.

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References

[1] P. Griffiths and R. Gillespie, "Shared control between human and machine: haptic display of automation during manual control of vehicle heading," in *12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2004. HAPTICS '04. Proceedings*, Mar. 2004, pp. 358 – 366.

[2] M. Mulder, D. A. Abbink, and E. R. Boer, "Sharing Control With Haptics: Seamless Driver Support From Manual to Automatic Control," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 54, no. 5, pp. 786–798, Oct. 2012.

[3] P. Marayong and A. M. Okamura, "Speed-Accuracy Characteristics of Human-Machine Cooperative Manipulation Using Virtual Fixtures With Variable Admittance," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 46, no. 3, pp. 518–532, 2004.

[4] M. Lam, M. Mulder, and van Paassen, "Haptic Interface in UAV Teleoperation using Force-stiffness Feedback," *International Conference on Systems, Man, and Cybernetics, San Antonio, TX, USA*, 2009.

[5] J. Smisek, E. Sunil, M. M. van Paassen, D. A. Abbink, and M. Mulder, "Neuromuscular-System-Based Tuning of a Haptic Shared Control Interface for UAV Teleoperation," *IEEE Transactions on Human-Machine Systems*, vol. PP, no. 99, pp. 1–13, 2016.

[6] D. A. Abbink and M. Mulder, "Neuromuscular analysis as a guideline in designing shared control," *Advances in haptics*, vol. 109, pp. 499–516, 2010.

[7] F. Flemisch, J. Kelsch, C. Löper, A. Schieben, and J. Schindler, "Automation spectrum, inner/outer compatibility and other potentially useful human factors concepts for assistance and automation," *2008, Human Factors for assistance and automation*, pp. 1–16, 2008.

[8] J. C. de Winter and D. Dodou, "Preparing drivers for dangerous situations: A critical reflection on continuous shared control," in *Systems, Man, and Cybernetics (SMC), 2011 IEEE International Conference on*. IEEE, 2011, pp. 1050–1056.

[9] D. W. v. d. Wiel, M. M. van Paassen, M. Mulder, M. Mulder, and D. A. Abbink, "Driver Adaptation to Driving Speed and Road Width: Exploring Parameters for Designing Adaptive Haptic Shared Control." IEEE, Oct. 2015, pp. 3060–3065.

[10] M. Itoh, F. Flemisch, and D. Abbink, "A hierarchical framework to analyze shared control conflicts between human and machine," *IFAC-PapersOnLine*, vol. 49, no. 19, pp. 96–101, Jan. 2016.

[11] C. Passenberg, A. Glaser, and A. Peer, "Exploring the Design Space of Haptic Assistants: the Assistance Policy Module," *IEEE Transactions on Haptics*, pp. 1–1, 2013.

[12] D. A. Abbink, M. Mulder, and E. R. Boer, "Haptic shared control: smoothly shifting control authority?" *Cognition, Technology & Work*, vol. 14, no. 1, pp. 19–28, Nov. 2011.

[13] M. D. Penna, M. M. van Paassen, D. A. Abbink, M. Mulder, and M. Mulder, "Reducing steering wheel stiffness is beneficial in supporting evasive maneuvers," in *IEEE International Conference on Systems Man and Cybernetics*, Istanbul, 2010, pp. 1628–1635.

[14] C. Passenberg, N. Stefanov, A. Peer, and M. Buss, "Enhancing task classification in human-machine collaborative teleoperation systems by real-time evaluation of an agreement criterion," in *World Haptics Conference (WHC), 2011 IEEE*, 2011, pp. 493–498.

[15] C. Passenberg, R. Groten, A. Peer, and M. Buss, "Towards real-time haptic assistance adaptation optimizing task performance and human effort," in *2011 IEEE World Haptics Conference (WHC)*, Jun. 2011, pp. 155 –160.

[16] A. Kucukyilmaz, T. M. Sezgin, and C. Basdogan, "Intention Recognition for Dynamic Role Exchange in Haptic Collaboration," *IEEE Transactions on Haptics*, vol. 6, no. 1, pp. 58–68, 2013.

[17] A. Mörtl, M. Lawitzky, A. Kucukyilmaz, M. Sezgin, C. Basdogan, and S. Hirche, "The role of roles: Physical cooperation between humans and robots," *The International Journal of Robotics Research*, vol. 31, no. 13, pp. 1656–1674, 2012.

[18] V. Duchaine and C. M. Gosselin, "General model of human-robot cooperation using a novel velocity based variable impedance control," in *EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2007. Second Joint*. IEEE, 2007, pp. 446–451.

[19] R. Riener, L. Lunenburger, S. Jezernik, M. Anderschitz, G. Colombo, and V. Dietz, "Patient-Cooperative Strategies for Robot-Aided Treadmill Training: First Experimental Results," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 13, no. 3, pp. 380–394, Sep. 2005.

[20] M. Zhang, M. Zhang, T. C. Davies, A. Nandakumar, and S. Xie, "An Assistance-as-Needed Control Paradigm for Robot-Assisted Ankle Rehabilitation," *Rehabilitation Process and Outcome*, p. 15, Mar. 2014.

[21] L. L. Cai, A. J. Fong, C. K. Otoshi, Y. Liang, J. W. Burdick, R. R. Roy, and V. R. Edgerton, "Implications of Assist-As-Needed Robotic Step Training after a Complete Spinal Cord Injury on Intrinsic Strategies of Motor Learning," *Journal of Neuroscience*, vol. 26, no. 41, pp. 10 564–10 568, Oct. 2006.

[22] H. U. Yoon, "Assistive HRI interface with perceptual feedback control: an approach to customizing assistance based on user dexterity," Ph.D. dissertation, University of Illinois at Urbana-Champaign, 2014.

[23] Y. Tanaka, N. Yamada, T. Tsuji, and T. Suetomi, "Vehicle Active Steering Control System Based on Human Mechanical Impedance Properties of the Arms," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 4, pp. 1758–1769, Aug. 2014.

[24] D. Aarno, S. Ekvall, and D. Kragić, "Adaptive virtual fixtures for machine-assisted teleoperation tasks," in *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*. IEEE, 2005, pp. 1139–1144.

[25] S. Ekvall, D. Aarno, and D. Kragic, "Online task recognition and real-time adaptive assistance for computer-aided machine control," *IEEE Transactions on Robotics*, vol. 22, no. 5, pp. 1029–1033, Oct. 2006.

[26] S. Nudehi, R. Mukherjee, and M. Ghodoussi, "A shared-control approach to haptic interface design for minimally invasive telesurgical training," *IEEE Transactions on Control Systems Technology*, vol. 13, no. 4, pp. 588–592, Jul. 2005.

[27] M. Desai and H. A. Yanco, "Blending human and robot inputs for sliding scale autonomy," in *Robot and Human Interactive Communication, 2005. ROMAN 2005. IEEE International Workshop on*. IEEE, 2005, pp. 537–542.

[28] M. B. Dias, B. Kannan, B. Browning, E. G. Jones, B. Argall, M. F. Dias, M. Zinck, M. M. Veloso, and A. J. Stentz, "Sliding autonomy for peer-to-peer human-robot teams," in *10th Intelligent Conference on Intelligent Autonomous Systems (IAS 2008), Germany*, 2008, pp. 332–341.

[29] A. D. Dragan and S. S. Srinivasa, "A policy-blending formalism for shared control," *The International Journal of Robotics Research*, vol. 32, no. 7, pp. 790–805, Jun. 2013.

[30] J. Smisek, W. Mugge, J. B. J. Smeets, M. M. van Paassen, and A. Schiele, "Adapting haptic guidance authority based on user grip," in *IEEE International Conference on Systems, Man and Cybernetics (SMC)*, San Diego, 2014, pp. 1516–1521.

[31] A. Tran, D. Liu, R. Ranasinghe, M. Carmichael, and C. Liu, "Analysis of Human Grip Strength in Physical Human Robot Interaction," *Procedia Manufacturing*, vol. 3, pp. 1442–1449, 2015.

[32] M. C. Baltzer, D. López, M. Kienle, and F. Flemisch, "Dynamic distribution of control via grip force sensitive devices in cooperative guidance and control," in *11. Berliner Werkstatt Mensch-Maschine-Systeme Conference*, Berlin, 2015.

[33] D. A. Abbink, "Task Instruction: the largest Influence on Human Operator Motion Control Dynamics," in *IEEE EuroHaptics Conference*, 2007, pp. 206–211.

[34] H. Nakamura, D. Abbink, and M. Mulder, "Is grip strength related to neuromuscular admittance during steering wheel control?" in *Systems, Man, and Cybernetics (SMC), 2011 IEEE International Conference on*, 2011, pp. 1658–1663.

[35] L. Bainbridge, "Ironies of automation," *Automatica*, vol. 19, no. 6, pp. 775–779, 1983.

[36] A. Field, *Discovering Statistics using IBM SPSS Statistics*. London: Sage, 2013.

[37] A. de Jonge, J. Wildenbeest, H. Boessenkool, and D. Abbink, "The Effect of Trial-by-trial Adaptation on Conflicts in Haptic Shared Control for Free-Air Teleoperation Tasks," *IEEE Transactions on Haptics*, pp. 1–1, 2015.

[38] J. van Oosterhout, J. G. W. Wildenbeest, H. Boessenkool, C. J. M. Heemskerk, M. R. de Baar, F. C. T. Van Der Helm, and D. A. Abbink, "Haptic Shared Control in Tele-Manipulation: Effects of Inaccuracies in Guidance on Task Execution," *IEEE Transactions on Haptics*, vol. 8, no. 2, pp. 164–175, Apr. 2015.

[39] J. Smisek, M. M. van Paassen, and A. Schiele, "Haptic guidance in bilateral teleoperation: Effects of guidance inaccuracy," in *IEEE World Haptics Conference*, Evanston, 2015, pp. 500–505.

[40] K. K. Tsoi, M. Mulder, and D. A. Abbink, "Balancing safety and support: Changing lanes with a haptic lane-keeping support system," in *Systems Man and Cybernetics (SMC), 2010 IEEE International Conference on*. IEEE, 2010, pp. 1236–1243.

[41] M. Li and A. M. Okamura, "Recognition of operator motions for real-time assistance using virtual fixtures," in *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003. Proceedings. 11th Symposium on*, 2003, pp. 125–131.

[42] Y. Li, J. C. Huegel, V. Patoglu, and M. K. O'Malley, "Progressive shared control for training in virtual environments," in *EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint*, 2009, pp. 332–337.

[43] D. Powell and M. K. O'Malley, "The Task-Dependent Efficacy of Shared-Control Haptic Guidance Paradigms," *IEEE Transactions on Haptics*, vol. 5, no. 3, pp. 208–219, 2012.

[44] T. Gibo and D. A. Abbink, "Movement Strategy Discovery During Training via Haptic Guidance," *IEEE Transactions on Haptics*, vol. 9, no. 2, pp. 243 – 254, 2016.

[45] S. Kimmer, J. Smisek, and A. Schiele, "Effects of Haptic Guidance and Force Feedback on Mental Rotation Abilities in a 6-DOF Teleoperated Task," in *IEEE International Conference on Systems, Man, and Cybernetics*, Kowloon, 2015, pp. 3092–3097.

Marinus M. (René) van Paassen received the M.Sc. degree (cum laude) from the Delft University of Technology, Delft, The Netherlands, in 1988, and a Ph.D. in 1994, both on studies into the neuromuscular system of the pilot's arm. He is an associate professor in Aerospace Engineering at the Delft University of Technology, working on human machine interaction and aircraft simulation. His work on human-machine interaction ranges from studies of perceptual processes, haptics and haptic interfaces and human manual control to design of and interaction with complex cognitive systems. René is a senior member of IEEE and of AIAA, and an associate editor for IEEE Transactions on Human-Machine System.

Jan Smisek received the M.Sc. degree in Systems and Control from the Czech Technical University in Prague, Czech Republic, in 2011, and his Ph.D. degree in Robotics at the Delft University of Technology, the Netherlands, in 2017. He is a Robotics Research Engineer at the Telerobotics and Haptics lab, with the European Space Research and Technology Centre (ESTEC) of the European Space Agency (ESA), situated in Noordwijk, the Netherlands. His research interests include human-machine interfaces, shared autonomy, and tele-operation with long time-delays.

André Schiele received his engineering degree in micro electro-mechanical systems in 2001 in Germany and his Ph.D. in mechanical engineering in 2008 from Delft University of Technology on the topic of robotic exoskeletons. He is currently an Associate Professor for Telerobotics & Advanced Mechatronics at Delft University of Technology. Since 2009 he has been founding Head of the ESA Telerobotics & Haptics Laboratory at the European Space Research and Technology Centre (ESTEC) in Noordwijk, the Netherlands. He is Principal Investigator of the METERON and HAPTICS spaceflight robotic technology demonstration projects. He has published over 50 papers on robotics, mechatronics, space robotics, telerobotics and haptics.

Winfred Mugge received the M.Sc. and Ph.D. degrees in mechanical engineering from Delft University of Technology, the Netherlands, in 2006 and 2011, respectively. During his PhD research at the Biomechanical Engineering Department, he performed research on muscle force feedback and movement disorders within Trauma Related Neuronal Dysfunction (TREND) and NeuroSIPE, Dutch multidisciplinary research consortia. From 2013 to 2015 he was a postdoctoral researcher at VU University Amsterdam and since then he has been working as an assistant professor at Delft University of Technology. His research interest is in neuromuscular control, haptics, system identification and includes techniques to quantify the functional contribution of afferent feedback.

Jeroen B. J. Smeets obtained in 1987 a M.Sc. degree in Experimental Physics at Utrecht University. At the same university, he obtained in 1991 a Ph.D. based on research on reflex coordination and the control of arm movements. Subsequently he became a post-doc and later staff member at the Department of Neuroscience of the Erasmus MC, Rotterdam. In 2006, he became full professor at the Department of Human Movement Sciences of the VU University, Amsterdam; since 2015 he is head of this department. His current teaching includes master courses on Concepts of Human Movement Sciences and on Perception in Action. His research spans a broad field sensorimotor control, ranging from visual and haptic perception to motor control. He is member of the editorial board of Acta Psychologica, Journal of Motor Behavior and Journal of Experimental Psychology- Human Perception and Performance.