Aalborg Universitet

Task-Dependent Adaptations in Closed-Loop Motor Control Based on Electrotactile Feedback

Dideriksen, Jakob L.; Mercader, Irene Uriarte; Dosen, Strahinja

Published in:
IEEE Transactions on Human-Machine Systems

DOI (link to publication from Publisher):
10.1109/THMS.2021.3134556

Publication date:
2022

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

Citation for published version (APA):
Dideriksen, J. L., Mercader, I. U., & Dosen, S. (2022). Task-Dependent Adaptations in Closed-Loop Motor Control Based on Electrotactile Feedback. *IEEE Transactions on Human-Machine Systems*, *52*(6), 1227-1235. Advance online publication. https://doi.org/10.1109/THMS.2021.3134556

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy
If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Task-Dependent Adaptations in Closed-Loop Motor Control Based on Electrotactile Feedback

Jakob L. Dideriksen, Irene Uriarte Mercader, and Strahinja Dosen

***Abstract*—Humans systematically adapt their strategies for closed-loop control based on visual feedback according to the dynamics of the system. Tactile feedback is a key element in many human–machine interfaces, but it is not known if and how well human control adapts to changes in system dynamics when information about the system state is provided using this type of feedback. In this study, 11 participants tracked a pseudorandom trajectory with a virtual, position- or velocity-controlled plant using a joystick. Visual or electrotactile feedback provided the instantaneous error between the target and generated trajectory. Frequency-domain system identification indicated that human control adapted in similar ways to the different control modes (i.e., position/velocity control) for both feedback modalities. For the plant dynamics modeled as gain and integrator, the human controller behaved as a low-pass filter and gain, respectively (under the assumption of quasi-linear behavior). However, while tracking quality was largely similar for both control modes with visual feedback, velocity control enabled substantially worse control with electrotactile feedback compared to position control. Furthermore, for both control modes, the crossover frequency of open-loop transfer functions was lower for electrotactile feedback (0.9 and 1.1 rad/s) than for visual feedback (1.5 and 1.7 rad/s) indicating limited control bandwidth. To summarize, closed-loop control based on electrotactile feedback enables natural adaptations in human control strategy, which is encouraging for tactile feedback-controlled human–machine interfaces, but the lower control bandwidth and lower tracking quality with velocity control may impose functional limitations.**

***Index Terms*—Closed-loop control sensory feedback, electrotactile stimulation, position control, sensory substitution, velocity control.**

I. Introduction

THE THEORY of human manual control refers to experimental and theoretical methods to investigate and model the behavior of a human subject controlling dynamic systems [1]. These approaches have been developed and used for decades to study human closed-loop control using visual feedback [2].

Manuscript received June 14, 2021; revised October 15, 2021; accepted December 1, 2021. This work was supported by the Independent Research Fund Denmark under Case 8022-00243A (ROBIN) and Case 8022-00226B. This article was recommended by Associate Editor X. Hu. *(Corresponding author: Jakob L. Dideriksen.)*

The authors are with the Department of Health Science and Technology, Aalborg University, 9220 Aalborg, Denmark (e-mail: jldi@hst.aau.dk; irene.uriartem@gmail.com; sdosen@hst.aau.dk).

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by North Denmark Region Committee on Health Research Ethics under Application No. N-20160021 and performed in line with the Declaration of Helsinki.

Digital Object Identifier 10.1109/THMS.2021.3134556

The application area for this type of research is vast, from steering ground vehicles to gaming and piloting. A typical experimental approach is a human-in-the-loop setup where subjects are asked to track a desired trajectory [3] using a chosen command interface [4]. The collected data are then used to estimate human performance and model the behavior of the human controller, where the latter captures how the subject responds to tracking errors [5].

One of the seminal results in this field was that human subjects could adapt their behavior to the dynamics of the system that they need to control [6]. More specifically, when modeled as a quasi-linear system, the transfer function of the human controller would change so that the overall transfer function of the controller and the plant corresponds to an integrator around the crossover frequency. Therefore, if the plant behaves as a gain, the human controller responds as a first-order lag, and vice versa, if the plant is an integrator, the human would act as a simple gain. Importantly, a plant that is represented by a gain or an integrator model corresponds to two widely used control paradigms in human–machine interfacing: position and velocity control, respectively. In the former, the human directly controls the position of the plant (e.g., a computer mouse), whereas, in the latter, the human command input sets the velocity of plant movement (e.g., gas pedal in a car).

However, a visual channel is not the only relevant source of feedback for control in human–machine interfaces. Specifically, in some situations, visual input is unavailable, limited, or absent if the user directs the visual attention away from the plant. In such situations, tactile feedback provided using mechanical (vibration motors, linear pushers, and squeezing braces [7]) or electrical stimulation of the skin can provide the information required to maintain control [8], [9]. Potential applications of tactile feedback include providing guidance for visually impaired persons [10], [11], improving immersiveness in virtual and augmented reality [12], as well as restoring missing somatosensory signals in prosthetic limbs [13]. Each of these application scenarios fit into the context of human manual control. For instance, in prosthesis control, the finger and wrist positions are controlled using velocity control since myoelectric activity sets the speed of movement, whereas the grasping force is controlled in the position mode (e.g., myoelectric level proportional to the grasping force). The performance across control schemes in feedforward control or with visual feedback has been investigated with mixed outcomes [14]–[16]. However, the properties of the human controller when the loop is closed using a tactile channel are much less explored compared to using visual feedback.

2168-2291 © 2021 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
See https://www.ieee.org/publications/rights/index.html for more information.

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on March 14,2022 at 08:45:38 UTC from IEEE Xplore. Restrictions apply.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

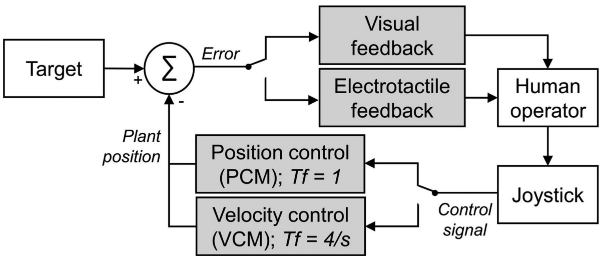

Fig. 1. Graphical representation of the experimental setup. The error between a predefined pseudorandom target and the instantaneous plant position was provided to the human operator as either visual or electrotactile feedback. Using a joystick, the human operator controlled the plant in position or velocity control (PCM/VCM) to minimize the error.

So far, the most complete investigation of such adaptations in human control based on haptic feedback was done by Jagacinski *et al.* where subjects controlled a virtual plant using a joystick with an in-built device coding the feedback in the physical displacement of a bar pushing into the subject's hand [17]. This study found that those subjects that performed best in controlling a plant in position and velocity control adapted their transfer function in the same ways as observed for visual feedback: a low-pass filter for position control and a gain for velocity control. In addition to this study, which investigated the full force feedback, only few other studies explored "pure" tactile feedback. Vibrotactile and air jets stimulation was evaluated in [18] demonstrating that the overall transfer function of the controller and a velocity-controlled plant resembled a low-pass filter. Closed-loop control with electrotactile stimulation was assessed in several studies [19]–[24] but they focused on characterizing performance without estimating the model of the human controller. To the best of our knowledge, just two studies reported the human transfer functions when using electrotactile feedback; however, only for position control mode, showing that the transfer functions resembled low-pass filters [25], [26]. The findings for tactile feedback are so far in agreement with the theory of human manual control, but as described above, the assessment was overall scarce. This is in sharp contrast to the fact that tactile interfaces are rich in stimulation and encoding methods, leading to feedback implementations that may be processed by the central nervous system in different ways. Consequently, it is not possible to draw general conclusions about task-dependent adaptations in human control based on tactile feedback; in particular, for electrotactile stimulation which is among the most commonly used feedback modalities. A deep understanding of if and how well human control adapts to different control paradigms with tactile feedback is critical for the design of effective closed-loop human–machine interfaces. For example, in the above-mentioned application scenario of prosthetic control, very few commercial prostheses currently offer tactile feedback; in part because there is no consensus about how such systems should be designed [13].

Therefore, in the present study, we investigated the impact of the system dynamics on the quality of closed-loop control using electrotactile feedback. We employed concentric electrodes, which are commonly used to deliver electrotactile stimulation since they produce superficial and confined current flow to elicit localized tactile sensations [27]. We assessed the performance and estimated the model of the human controller in both control modes (position versus velocity) when the feedback was delivered using encoding in stimulation frequency. While most previous studies employed amplitude modulation (e.g., [19]–[22]), frequency modulation was selected since we have shown that it enables superior performance in the same type of closed-loop control task as used in this study [26]. Our *a priori* expectation was that a human controller adapts to different plant dynamics using electrotactile feedback in the same way it adapts when the feedback is transmitted visually. Furthermore, we assessed if both control modes lead to similar control performance.

II. Methods

A. Participants

Eleven able-bodied participants (5 males and 6 females, age: 26 ± 3 years) performed the experiment. The participants signed an informed consent form before the experiment. The experiment complied with the declaration of Helsinki and was approved by the North Denmark Region Committee on Health Research Ethics (N-20160021).

B. Experimental Setup

The experimental setup implemented a human-in-the-loop approach where the participant controlled the position or velocity of a virtual plant based on visual or electrotactile feedback (see Fig. 1). The plant was controlled by moving a joystick (APEM HF22X10U) around a single axis (left/right) with the dominant hand. The feedback was given on a computer screen positioned approximately 50 cm in front of the subject (visual condition), or by a stimulation unit (TremUNA, UNA Systems, Belgrade, Serbia) activating two concentric electrodes (Spes Medica 50 mm × 50 mm) positioned on each side of the forearm of the dominant hand (electrotactile condition). The aim was to control the plant so that its position followed a predefined reference trajectory. However, the trajectory was not disclosed to the subject explicitly. Instead, both types of feedback conveyed to the participant the instantaneous error between the plant position and a predefined target trajectory. This is a so-called compensatory tracking paradigm [6], in which the task performance depended exclusively on the participant's reaction to the stimulus and not on anticipatory control.

Using the joystick, the participant determined the position of the virtual plant in either position control mode (PCM) or velocity control mode (VCM). In PCM, the position of the joystick was proportional to the plant position. In this way, moving the joystick fully to the left implied that the plant was in the maximum left-most position and vice versa for the right. In VCM, the position of the joystick determined the velocity of the plant, and so a constant nonzero joystick position implied a constant plant velocity in either left or right direction. In PCM, the transfer function of the plant was a gain. For VCM, the transfer function was an integrator with a gain. The values of both gains were determined in pilot tests as the configurations that

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on March 14,2022 at 08:45:38 UTC from IEEE Xplore. Restrictions apply.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

optimally allowed rapid but well-controlled plant movement. In both modes, the plant position was limited in the range of [−1:1] in arbitrary units. The normalized plant position was mapped to the normalized visual and electrotactile feedback, as described in the following.

The target trajectory was a pseudorandom signal formed by the sum of nine sinusoids with logarithmically spaced frequencies between 0.2 and 6.3 rad/s. Across trials, the phase of each sine wave was assigned a new random value. The range of sine wave frequencies is similar to the ranges used in previous studies (see [18, Table I]). The amplitudes of the five sine waves with lowest frequencies ($\leq$1 rad/s) were twice as high as the amplitude of the other four sine waves to decrease the task difficulty while maintaining the desired bandwidth. For compensatory tracking tasks with visual feedback, a larger difference (factor of 10) between low- and high-frequency components has been used traditionally [28]. However, to reduce the risk that the magnitude of the high-frequency sine waves would be below the just noticeable difference for the frequency of electrotactile feedback, a lower factor was used in this study, similarly as in previous studies with tactile feedback [17], [26]. The amplitude of the target trajectory was normalized to the range of [−0.9:0.9] in arbitrary units.

With visual feedback, the instantaneous error was represented as a cursor (green square) shown on a horizontal axis. In the middle of the axis, a reference line indicated an error of zero. With electrotactile feedback, the magnitude of the error was coded in the frequency of stimulation pulses in one of the two electrodes, depending on the sign of the error. As in our previous study [26], one electrode (ventral side) communicated negative errors, while the other electrode (dorsal side) communicated positive errors. The normalized tracking error was mapped linearly to a range of stimulation frequencies of 7-63 Hz. In this way, 63 Hz implied maximum error, while perfect tracking (i.e., no error) would imply no stimulus in any of the electrodes. Frequency modulation in this range was selected because we have demonstrated in a recent study [26] that it leads to better performance compared to intensity modulation. In addition, the ability of humans to differentiate stimulation frequencies decrease at higher frequencies [29].

The stimulation parameters and timing as well as the visual feedback were controlled using a toolbox for closed-loop human manual control [30] running on a standard PC.

C. Experimental Protocol

The participant was seated comfortably in a chair in front of a table with the experimental setup (joystick, stimulator, and PC). The skin on the forearm was cleaned using a wet cloth, and the stimulation electrodes were placed. One electrode was positioned on the ventral side of the forearm halfway between the elbow and the wrist. The other electrode was positioned on the dorsal side, one-third of the length of the forearm distally from the elbow. For each electrode, the detection and pain threshold for stimulation pulsewidth were determined using the method of limits [31]. The pulsewidth was incremented in the steps of 10 μs at a stimulation frequency and amplitude of 70 Hz and 3.5 mA, respectively. When the subject reported that she/he felt the stimulation (detection threshold), the increment was increased to 50 μs and the stimulation stopped when the subject indicated that it became painful. This intensity corresponded to the pain threshold. The thresholds were determined three times and the average value was computed.

Next, the participant was familiarized with the tracking tasks using visual feedback. The participant was instructed to move the joystick to cancel the tracking error by maintaining the cursor indicating the plant position, as close as possible to the reference line. The subjects received no instructions about which strategies could be applied for joystick control (e.g., continuous or "tapping" movements) and were left to explore such strategies themselves during the familiarization trials. First, each participant performed two 90-s trials with PCM followed by two trials with VCM. This was followed by two trials for each control mode (PCM and VCM) with visual and electrotactile feedback delivered simultaneously. The aim here was for the subject to learn to interpret the electrotactile feedback associating it to the tracking error shown visually. The subject was instructed to compensate for the delivered stimulation, e.g., if he/she felt it on the dorsal electrode, he/she would move the joystick in the direction of the volar electrode and vice versa. It was also explained that faster stimulation indicates larger errors. Finally, another two trials were conducted per control mode with electrotactile feedback only. In the trials with electrotactile feedback, the stimulation pulsewidth was set to a duration of 80% of the width at the pain threshold. This value was selected to elicit a clear but nonpainful sensation.

After the training trials, the participants started the closed-loop tracking. The experiment was organized into four blocks (2 feedback types $\times$ 2 control modes), where each block included six 90-s trials. The order of the four blocks (each consisting of six trials) was randomized. The six trials within the same block were separated by a break of at least 1 min, and a break of 5 min was given between blocks. For each trial (including familiarization trials), a new target trajectory was randomly generated to avoid that the subjects switched to feedforward control by learning to predict the trajectory.

D. Data Analysis

Four time-domain parameters were derived from the tracking data in each trial. First, the cross-correlation between the target and plant trajectory was computed to quantify the similarity between the target and plant trajectories. The peak of this function (henceforth referred to as correlation) and the time delay at this peak were identified. Note that the time delay is an estimate of the time shift between the two trajectories, which is different from the time delay of the human controller (described later). Furthermore, the root-mean-square error (RMSE) between the target and the plant trajectory was calculated, after compensating for the time delay between these two signals. This compensation was done since even a small delay would imply a large RMSE for very similar trajectories. Together, these three parameters characterized the quality of the tracking performance. The fourth time-domain parameter characterized

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on March 14,2022 at 08:45:38 UTC from IEEE Xplore. Restrictions apply.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

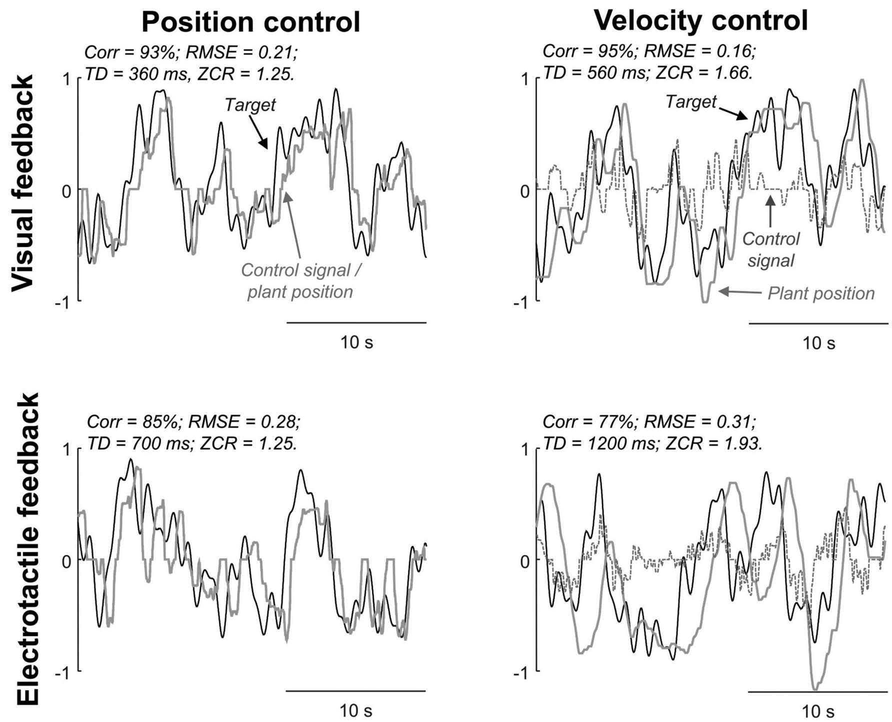

Fig. 2. Representative tracking data for one participant (subject #10) across the four conditions (2 feedback types × 2 control modes). Each panel represents a 30-s period from the last of the six trials in one of the conditions. In all panels, the black line indicates the pseudorandom target trajectory. For position control, the gray lines indicate the control signal (joystick output) and plant position (equivalent in position control). For velocity control, the control signal is shown as the dashed gray line, whereas the plant position is the solid gray line. All signals are provided in arbitrary units. Each panel also reports correlation (Corr), RMSE, time delay (TD), and zero-crossing rate for the first derivative of the control signal (ZCR) achieved in each case.

the tracking strategy. Specifically, the rate of zero crossings in the first derivative of the joystick output signal was obtained to characterize how often the subject changed the direction in which she/he moved the joystick. Before this analysis, the joystick output signal was low-pass filtered (cutoff frequency: 2.5 Hz).

The data were normally distributed, as determined using the Shapiro–Wilk test. Therefore, the outcome measures were analyzed using three-way ANOVA (factors: trial, feedback type, and control mode) for each of the four time-domain parameters. The level of significance was set to $p < 0.013$ due to the Bonferroni correction. In case of significant interaction effects between two of these factors, the average value across the third factor for each of the two interaction factors was compared using paired t-test. For the outcome of the ANOVA analysis, effect sizes were estimated using partial η^2. The values 0.01, 0.06, and 0.14 were adopted as lower limits for small, medium, and large effect sizes, respectively. Furthermore, the correlation between the zero-crossing rate and the three other time-domain parameters were investigated using linear regression for each combination of control mode and feedback type.

In addition, frequency-domain analysis was performed to estimate the frequency characteristics of the human controller across the four conditions (2 feedback types × 2 control modes) using a previously described method [26], [32]. To summarize, the frequency characteristics of the human controller (assuming that it is quasi-linear) were determined by calculating the ratio of the cross-spectrum between the target and plant trajectories and between the target trajectory and the error. This provided an estimate of the gain and phase characteristics of the human controller for each of the nine frequencies that comprised the target trajectory. For each control mode and feedback modality, a transfer function was fitted to the average frequency response across all subjects. The gain and time delay of the human controller were estimated from the fitted function. While this delay characterizes the reaction time of the human subject, the delay computed in the time-domain analysis is between the input and output of the overall system. Therefore, the latter includes the time shift due to the pure time delay of the human controller as well as the offset introduced by the system dynamics of the human and the controlled plant. Furthermore, the open-loop transfer functions were computed by multiplication of the transfer function of the human controller and the transfer function of the plant. The latter was used to estimate the crossover frequency, representing the effective control bandwidth (i.e., the maximum error signal frequency that can be successfully perceived and compensated by the subject) and the phase margin quantifying whether the system is stable and how far it is from the margin of stability. These are standard parameters to describe the model of the human controller [6].

III. Results

Fig. 2 shows representative data from the last (sixth) trials for different combinations of control mode (PCM and VCM) and feedback (visual and electrotactile) for one subject. For

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on March 14,2022 at 08:45:38 UTC from IEEE Xplore. Restrictions apply.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

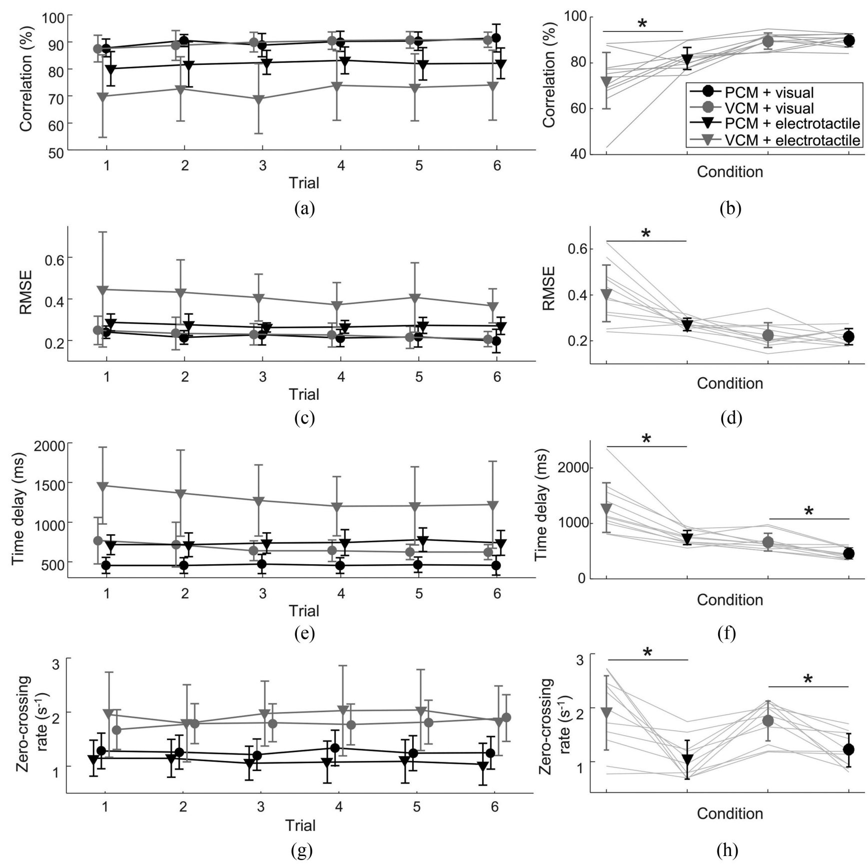

Fig. 3. Four time-domain parameters describing tracking performance and strategy: (a) and (b) Correlation, (c) and (b) RMSE, (e) and (f) time delay, and (g) and (h) zero-crossing rate for the first derivative of the joystick control signal. In panels (a), (c), (e), and (g), the average parameters for all subjects are shown across the six trials for each of the four conditions. Panels (b), (d), (f), and (h) show average values across the six trials of individual subjects (light gray lines) and across all subjects (symbols). In all panels, error bars indicate standard deviation. *indicate statistical significance.

PCM, the plant position (generated trajectory) was proportional to the control signal (joystick movement), whereas in VCM, the integrated joystick position determined the position of the plant. The control strategies applied in VCM varied across subjects and conditions. Some subjects controlled the plant by a series of rapid taps to the joystick with varying amplitude, whereas others, like the subject shown in Fig. 2, used a higher degree of continuous joystick control. Note, however, that even in this case, the continuous modulation was supplemented with tapping-like movements that are not present in PCM. Therefore, the subject has substantially changed the control approach between the two modes. The employed control signals (joystick movements) in Fig. 2 for PCM are substantially different from those in VCM (e.g., compare smooth modulation in the top-left panel to abrupt left/right deviations in the bottom-left panel). In the representative subject, the two control modes enabled control of approximately the same quality for visual feedback. For electrotactile feedback, however, PCM enabled better control, although, for both modes, the control was worse than for visual feedback.

This trend was confirmed by Fig. 3, which illustrates the average results across all subjects and trials for the feedback and control modes. Overall, the performance with electrotactile feedback was consistently better during PCM than VCM, whereas control mode had only a minor effect on performance in the case of visual feedback. Specifically, for electrotactile feedback, average correlation was 9.6 percentage points higher, average RMSE was 0.14 lower, and average time delay was 541 ms shorter with PCM than for VCM. Conversely, for visual feedback, the average differences across control modes were much smaller: 0.26 percentage points (correlation), 0.006 (RMSE), and 204 ms (time delay). As illustrated in Fig. 2, the zero-crossing rate of the control signal was lowest in PCM. Specifically, the difference was 0.84 and 0.53 zero crossings per second for electrotactile and visual feedback, respectively. For all parameters, ANOVA indicated significant effects of control mode [correlation: $p<0.013$ partial η^2: 0.10 (medium effect size); RMSE: $p<0.013$ partial η^2: 0.14 (large effect size); time delay: $p<0.013$ partial η^2: 0.33 (large effect size); $p<0.013$; partial η^2: 0.35 (large effect size)] and significant interaction effects between feedback type and control mode for all parameters but the zero-crossing rate [correlation: $p<0.013$; partial η^2: 0.09 (medium effect size); RMSE: $p<0.013$; partial η^2: 0.12 (medium effect size); time delay: $p<0.013$; partial η^2: 0.09 (medium effect size)]. This indicates that the significant effects of control mode could be attributed mainly to the differences in electrotactile feedback. This was confirmed by the t-tests, that showed significant differences across control modes only for electrotactile

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on March 14,2022 at 08:45:38 UTC from IEEE Xplore. Restrictions apply.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

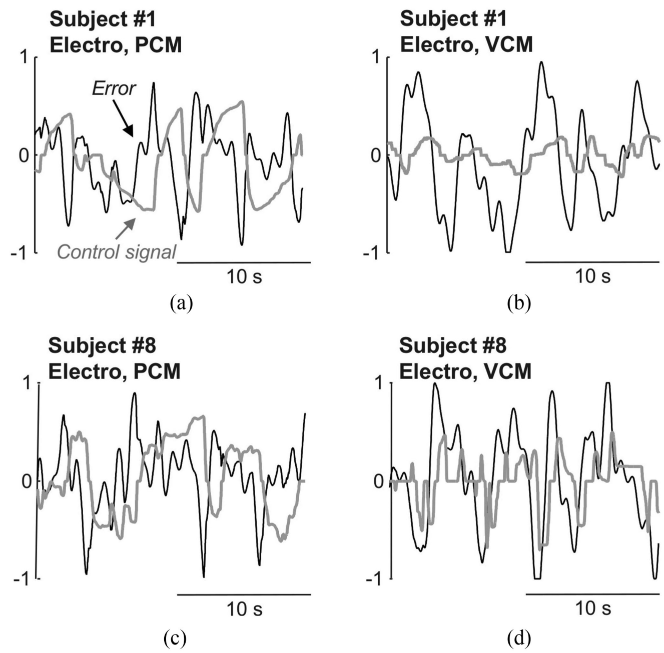

Fig. 4. Representative examples of how subjects responded to the error signal received by electrotactile stimulation in PCM (A, C) and VCM (B, D) during the sixth trial in each condition. In all panels, the black line indicates the instantaneous tracking error and the gray line the control signal (joystick output).

feedback for correlation [$p<0.013$ for electrotactile; $p = 0.87$ for visual; Fig. 3(b)] and RMSE [$p<0.013$ for electrotactile; $p = 0.73$ for visual; Fig. 3(d)]. For time delay and zero-crossing rate, however, the differences in control mode were significant ($p<0.013$) for both feedback types [see Fig. 3(f)].

For all time-domain parameters except the zero-crossing rate, there were significant effects of feedback type (correlation: $p<0.013$ partial η^2: 0.42 (large effect size); RMSE: $p<0.017$ partial η^2: 0.31 (large effect size); time delay: $p<0.017$ partial η^2: 0.43 (large effect size); zero-crossing rate: $p = 0.82$). Specifically, the correlation was 77.1% for electrotactile (averaged across all trials and control modes) and 89.6% visual feedback, average RMSE was 0.34 for electrotactile feedback and 0.22 for visual feedback, and time delay was 1016 ms for electrotactile and 562 ms for visual feedback. Finally, the three-way ANOVA revealed that there was no significant learning effect across the six trials for any of the parameters, nor any interaction effects involving learning.

The zero-crossing rate did not predict any of the other time-domain parameters (correlation, RMSE, and time delay) in any of the settings ($r^2<0.15$), indicating that the control strategy employed by the subjects did not affect the quality of the outcome.

Fig. 4 illustrates the strategy by which the subjects compensated for the tracking error when it was transmitted using electrotactile stimulation. The plots superimpose the error signal and the joystick position, which correspond to the input into the human controller and his/her response (output), respectively. When these representative subjects controlled the plant in PCM, the control signal appeared to be a substantially smoothed (and

TABLE I
CROSSOVER FREQUENCY AND PHASE MARGIN FOR THE ESTIMATED OPEN-LOOP TRANSFER FUNCTIONS FOR EACH COMBINATION OF FEEDBACK MODALITY AND CONTROL MODE

	Visual		*Electrotactile*	
	PCM	VCM	PCM	VCM
Cross-over frequency (rad/s)	1.46	1.72	0.85	1.06
Phase margin (degrees)	98.4	60.0	92.9	61

delayed) version of the error. As predicted by the theory of human manual control [1], the control signal in VCM reflected more faithfully the dynamics of the error signal. These characteristics were also reflected in the average frequency characteristics of all subjects (see Fig. 5). The figure shows that the human controllers acted like low-pass filters for PCM (magnitude decreases with frequency) and as gains for VCM (magnitude constant across frequencies). This trend was expected for the trials with visual feedback, but it has not been previously demonstrated that qualitatively similar adaptations in human behavior are present when controlling an object using electrotactile stimulation [see Fig. 5(b)]. With respect to compensatory tracking with visual feedback, electrotactile feedback implied a lower gain of the human controller—in particular for VCM. Specifically, for VCM, the average gain across all frequencies was -7.4 ± 1.3 dB for visual feedback and -12.6 ± 1.0 dB for electrotactile feedback. Phase characteristics were largely similar across conditions, with the exception that electrotactile feedback implied a larger phase delay at the highest frequencies. Accordingly, the transfer functions [see Fig. 5(c) and (d)] indicated a larger time delay for electrotactile feedback [190 (PCM) and 130 ms (VCM) for visual feedback against 320 (PCM) and 340 (VCM) ms for electrotactile feedback]. Furthermore, this is in accordance with the results of the time-domain analysis considering that the higher controller gain indicates better tracking while the steeper phase roll-off reflects a longer time delay in responding to the input (error signal). Table I summarizes the characteristics of the open-loop transfer functions.

IV. DISCUSSION

This study investigated how human closed-loop control based on electrotactile feedback, delivered using concentric electrodes and frequency modulation, adapts to different dynamics of the controlled system (PCM/VCM). Overall, the results demonstrated that the control strategies adapt as predicted by the theory of human manual control [1], [28]. Visual feedback provides high-fidelity information on the behavior of the controlled object and therefore it is not surprising that the subject can perceive the change in the plant dynamics and adapt his/her control strategy. Electrotactile stimulation is a feedback channel of lower quality, but the present study demonstrates that it is still informative enough to provoke a similar type of adaptation during manual control. In that sense, the electrotactile interface mirrors the behavior of other tactile stimulation methods (vibrotactile and air jets [18] and full kinesthetic force feedback [17]). This is an

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on March 14,2022 at 08:45:38 UTC from IEEE Xplore. Restrictions apply.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

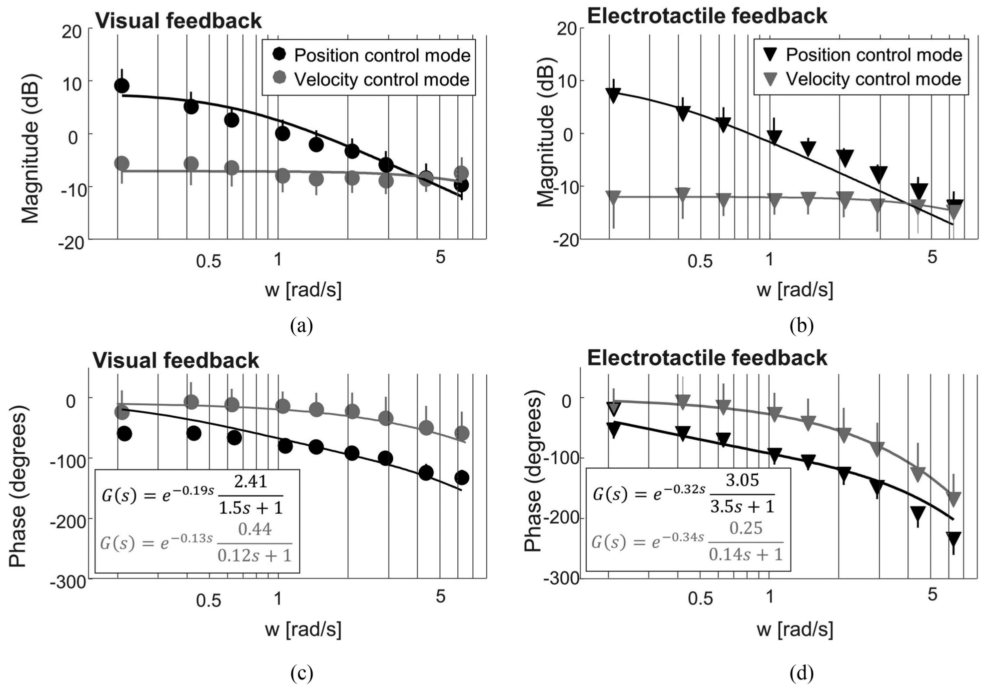

Fig. 5. Frequency response of the human controller across the four control conditions for all trials of all participants. Each symbol represents (a) and (b) magnitude and (c) and (d) phase delay for each of the nine frequencies composing the target signal. Bold lines representing the estimated transfer functions are superimposed. Error bars (shown only in one direction) indicate standard deviation.

encouraging result for the practical application of this type of feedback, as elaborated later.

The results showed that while control quality with visual feedback was similar in both control modes, velocity control imparted significantly worse performance than position control for electrotactile feedback. In principle, velocity control is more complex compared to the position control. The higher complexity can be appreciated by focusing on a simple task of commanding a plant to change the position. When using position control, the subject needs to move the control interface from the initial to the target position and then hold it there. To achieve the same using velocity control, however, the subject first has to move the control interface to command a nonzero velocity toward the target. Then, once the plant is at the target position, he/she needs to bring the control back to zero so that the target stops moving (hence, two command actions to accomplish the same goal). When this is placed in the context of a compensatory tracking task, which requires reacting rapidly to a dynamically changing input, the differences between the two control modes are more likely to become expressed. Nevertheless, visual feedback appeared to provide sufficiently rich information about the state of the plant that required a low cognitive load to process, which allowed the subject to perform equally well in both control modes. On the contrary, the control with the tactile feedback was not robust enough and a (small) change in control complexity was enough to significantly decrease the performance. This conclusion is, of course, specific to the bandwidth of the target trajectory used in the present study. Increasing the bandwidth might introduce differences in the quality of control even when using visual feedback, while a narrower bandwidth may enable similar performance across control modes with electrotactile feedback. Nevertheless, this finding is in accordance with previous results that showed that subjects have less excess cognitive capacity when using tactile feedback for control [33]. The tracking performance was variable across subjects, especially when the task was performed using electrotactile feedback, where the across-subject variability seems to be larger for PCM than VCM. This is in line with the higher difficulty of that task as well as with the recent observation that the subjects can differ substantially in how well they can integrate the electrotactile feedback [34].

Overall, the quality of control with electrotactile feedback was worse than with visual feedback. This finding is in accordance with previous studies using similar tasks [17], [35] and may in part reflect that with visual feedback allows for a quick and accurate estimation of the tracking error, whereas several stimulation pulses (and thus longer time) are needed to perceive the error with frequency-modulated electrotactile stimulation. Nevertheless, we have previously shown that the time delay does not change when the error is encoded in the pulsewidth of electrotactile feedback [26], which could be due to intrinsic limitations of the human control bandwidth [36]. Despite this difference across visual and electrotactile feedback, the present study demonstrated that it is feasible to utilize the velocity control using electrotactile stimulation. As can be seen from Fig. 2(d), despite obvious delays and deviations, the subject has successfully reproduced the general shape of the target trajectory, while largely ignoring the small wiggles. Furthermore, although there was no statistically significant effect of learning, the performance in velocity control with electrotactile feedback improved for all three measures (see Fig. 3) across the

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on March 14,2022 at 08:45:38 UTC from IEEE Xplore. Restrictions apply.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

six trials. It is possible that extended periods of training may reduce the difference across control modes with electrotactile feedback [37]–[39]. Finally, the experimental task of this study was specifically designed to allow only feedback control. However, in most everyday motor tasks, a combination of feedback and feed-forward control is used [13], [40], which makes it reasonable to assume that performance could be improved if it is possible to plan movements ahead. Accordingly, in tasks similar to the one used in the present study, the knowledge of the future target trajectory improved performance [41].

In comparison with previous studies, the crossover frequencies (see Table I) were relatively low for visual feedback [28] and mechanical tactile feedback [17]. However, in these studies, the subjects were either highly skilled or had undergone intensive training for several days. Conversely, naïve subjects with minimal training (12 $\times$ 90 s trials) were used in this study. The open-loop system characteristics (see Table I) were similar to those reported for tactile feedback in a previous study in which the subjects also received limited training [18]. Overall, this result (see Fig. 5) indicates that when introduced to electrotactile feedback, subjects immediately adopt the control strategies described by the theory of human manual control, and that further training only serves to refine this strategy to improve performance.

The impact of system dynamics (gain versus integrator) on the performance with electrotactile feedback is a relevant result since position and velocity control are commonly used in different application scenarios. Such scenarios include closed-loop prosthetic control, where recent methods have been proposed to eliminate the contamination of electromyographic (EMG) signals by electrotactile stimulation [42]. Note that there is comprehensive body of literature addressing prosthesis control with and without feedback in more clinical and functional context [13], [43]. The present paper however reveals some fundamental aspects of tactile feedback that might be relevant across application domains. This is also the motivation for adopting an abstract task rather than focusing on a specific system (e.g., a particular prosthetic device or a functional AR/VR task). Specifically, this study suggests that electrotactile feedback allows humans to adapt control strategies in a natural way. However, the control quality of these strategies is limited in several ways including the effective bandwidth. Specifically, the crossover frequency was considerably lower than for visual feedback (see Table I), as well as the values reported for natural control of hand movement [44]. Current prostheses generally have a low control bandwidth, due to the mechanical design and the preprocessing (low-pass filtering) of the EMG signal [45], but future prosthetic control systems may not have such limitations. If so, the low crossover frequency in closed-loop control with electrotactile feedback may be an important limitation for high-quality control, suggesting the need to identify feedback strategies with higher bandwidth. The experimental approach presented in this study can be used to systematically compare feedback strategies to identify those that optimally support performance in VCM. In this context, this setup may be extended to simulate more complex systems reflecting the characteristics of human–machine interfaces more realistically. For example, controlling a prosthesis implies a time lag between control command and prosthesis response due to internal data processing (e.g., pattern classification) and mechanical design [46]. It is possible that such delays would increase the complexity of the task and increase the difference in performance across control modes observed in this study (see Fig. 3). Furthermore, since prostheses are typically controlled by myoelectric signals, which are inherently noisy, it would be relevant to explore the effect of using a less ideal control interface than a joystick (see [4] for a similar comparison using visual feedback). Finally, it would be relevant to investigate combined tactile and visual feedback, since in a realistic scenario, prosthesis users would probably devote some level of visual attention to most tasks and not always rely exclusively on tactile feedback.

In conclusion, this study demonstrates that humans are capable of adapting motor control strategies based on electrotactile feedback according to the dynamics of the controlled system (position/velocity control) in similar ways as for visual feedback (theory of human manual control). The quality of control with electrotactile feedback in VCM, however, was lower than that in PCM.

References

[1] D. Mcruer and D. H. Weir, "Theory of manual vehicular control," *IEEE Trans. Man-Mach. Syst.*, vol. MMS-10, no. 4, pp. 257–291, Dec. 1969.

[2] M. Mulder *et al.*, "Manual control cybernetics: State-of-the-art and current trends," *IEEE Trans. Hum.-Mach. Syst.*, vol. 48, no. 5, pp. 468–485, Oct. 2018.

[3] K. Van Der El, D. M. Pool, M. M. Van Paassen, and M. Mulder, "Effects of target trajectory bandwidth on manual control behavior in pursuit and preview tracking," *IEEE Trans. Hum.-Mach. Syst.*, vol. 50, no. 1, pp. 68–78, Feb. 2020.

[4] J. Lobo-Prat, A. Q. L. Keemink, A. H. A. Stienen, A. C. Schouten, P. H. Veltink, and B. F. J. M. Koopman, "Evaluation of EMG, force and joystick as control interfaces for active arm supports," *J. Neuroeng. Rehabil.*, vol. 11, 2014, Art. no. 68, doi: 10.1186/1743-0003-11-68.

[5] H. J. Damveld, G. C. Beerens, M. M. Van Paassen, and M. Mulder, "Design of forcing functions for the identification of human control behavior," *J. Guid. Control Dyn.*, vol. 33, no. 4, 2010, Art. no. 122677651, doi: 10.2514/1.47730.

[6] R. J. Jagacinski and J. M. Flach, *Control Theory for Humans*. Boca Raton, FL, USA: CRC Press, 2018.

[7] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives," *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 580–600, Oct.–Dec. 2017.

[8] A. Y. J. Szeto and F. A. Saunders, "Electrocutaneous stimulation for sensory communication in rehabilitation engineering," *IEEE Trans. Biomed. Eng.*, vol. BME-29, no. 4, pp. 300–308, Apr. 1982.

[9] L. A. Jones and N. B. Sarter, "Tactile displays: Guidance for their design and application," *Hum. Factors*, vol. 50, no. 1, pp. 90–111, 2008, doi: 10.1518/001872008X250638.

[10] J. Loomis, R. Klatzky, and N. Giudice, "Sensory substitution of vision: Importance of perceptual and cognitive processing," in *Assistive Technology for Blindness and Low Vision*, R. Manduchi and S. Kurniawan, Eds. Boca Raton, FL, USA: CRC Press, 2012.

[11] H. C. Stronks, E. B. Mitchell, A. C. Nau, and N. Barnes, "Visual task performance in the blind with the Brainport V100 vision aid," *Expert Rev. Med. Devices*, vol. 13, no. 10, pp. 919–931, 2016, doi: 10.1080/17434440.2016.1237287.

[12] D. S. Pamungkas and K. Ward, "Electro-tactile feedback system to enhance virtual reality experience," *Int. J. Comput. Theory Eng.*, vol. 8, no. 6, pp. 465–470, 2016, doi: 10.7763/ijcte.2016.v8.1090.

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on March 14,2022 at 08:45:38 UTC from IEEE Xplore. Restrictions apply.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

[13] J. W. Sensinger and S. Dosen, "A review of sensory feedback in upper-limb prostheses from the perspective of human motor control," *Front. Neurosci.*, vol. 14, 2020, Art. no. 345, doi: 10.3389/fnins.2020.00345.

[14] S. Mick, D. Cattaert, F. Paclet, P.-Y. Oudeyer, and A. de Rugy, "Performance and usability of various robotic arm control modes from human force signals," *Front. Neurorobot.*, vol. 11, Oct. 2017, Art. no. 55, doi: 10.3389/FNBOT.2017.00055.

[15] "Volitional control of target position using sonomyography," Accessed: Aug. 26, 2021, 2020. [Online]. Available: https://www.resna.org/sites/default/files/conference/2020/StudentScientificPapers/NewAndEmergingTechnology/129Patwardhan.html

[16] J. L. Segil and R. F. Weir, "Novel postural control algorithm for control of multifunctional myoelectric prosthetic hands," *J. Rehabil. Res. Dev.*, vol. 52, no. 4, pp. 449–466, 2015, doi: 10.1682/JRRD.2014.05.0134.

[17] R. J. Jagacinski, J. M. Flach, and R. D. Gilson, "A comparison of visual and kinesthetic—Tactual displays for compensatory tracking," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-13, no. 6, pp. 1103–1112, Nov./Dec. 1983.

[18] J. W. Hill, "A describing function analysis of tracking performance using two tactile displays," *IEEE Trans. Man-Mach. Syst.*, vol. MMS-11, no. 1, pp. 92–101, Mar. 1970.

[19] T. R. Schori, "Tracking performance as a function of precision of electrocutaneous feedback information," *Hum. Factors J. Hum. Factors Ergonom. Soc.*, vol. 12, no. 5, pp. 447–452, 1970, doi: 10.1177/001872087001200503.

[20] L. P. Paredes, S. Dosen, F. Rattay, B. Graimann, and D. Farina, "The impact of the stimulation frequency on closed-loop control with electrotactile feedback," *J. Neuroeng. Rehabil.*, vol. 12, no. 1, 2015, Art. no. 35, doi: 10.1186/s12984-015-0022-8.

[21] S. Dosen, M. Schaeffer, and D. Farina, "Time-division multiplexing for myoelectric closed-loop control using electrotactile feedback," *J. Neuroeng. Rehabil.*, vol. 11, 2014, Art. no. 138.

[22] M. A. Hofmann and N. W. Heimstra, "Tracking performance with visual, auditory, or electrocutaneous displays," *Hum. Factors*, vol. 14, no. 2, 1972, pp. 131–138, doi: 10.1177/001872087201400202.

[23] L. F. Engels, A. W. Shehata, E. J. Scheme, J. W. Sensinger, and C. Cipriani, "When less is more-discrete tactile feedback dominates continuous audio biofeedback in the integrated percept while controlling a myoelectric prosthetic hand," *Front. Neurosci.*, vol. 13, 2019, Art. no. 578, doi: 10.3389/fnins.2019.00578.

[24] G. Risso *et al.*, "Optimal integration of intraneural somatosensory feedback with visual information: A single-case study," *Sci. Rep.*, vol. 9, no. 1, 2019, Art. no. 7916, doi: 10.1038/s41598-019-43815-1.

[25] H. P. Schmid and G. A. Bekey, "Tactile information processing by human operators in control systems," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-8, no. 12, pp. 860–866, Dec. 1978.

[26] J. Dideriksen, I. Mercader, and S. Dosen, "Closed-loop control using electrotactile feedback encoded in frequency and pulse width," *IEEE Trans. Haptics*, vol. 13, no. 4, pp. 818–824, Oct.–Dec. 2020.

[27] A. Higashiyama and M. Hayashi, "Localization of electrocutaneous stimuli on the fingers and forearm: Effects of electrode configuration and body axis," *Perception Psychophys.*, vol. 54, pp. 108–120, 1993, doi: 10.3758/BF03206942.

[28] D. T. McRuer, D. Graham, and E. S. Krendel, "Manual control of single-loop systems: Part I," *J. Franklin Inst.*, vol. 283, no. 1, pp. 1–29, Jan. 1967, doi: 10.1016/0016-0032(67)90112-3.

[29] J. A. George, M. R. Brinton, P. C. Colgan, G. K. Colvin, S. J. Bensmaia, and G. A. Clark, "Intensity discriminability of electrocutaneous and intraneural stimulation pulse frequency in intact individuals and amputees," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2020, pp. 3893–3896, doi: 10.1109/EMBC44109.2020.9176720.

[30] S. Dosen, M. Markovic, C. Hartmann, and D. Farina, "Sensory feedback in prosthetics: A standardized test bench for closed-loop control," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 23, no. 2, pp. 267–276, Mar. 2015.

[31] F. Kingdom and N. Prins, *Psychometrics: A Practical Introduction*. Cambridge, MA, USA: Academic, 2009.

[32] D. T. McRuer and E. S. Krendel, "The human operator as a servo system element," *J. Franklin Inst.*, vol. 267, no. 5, pp. 381–403, 1959.

[33] T. R. Schori, "A comparison of visual, auditory, and cutaneous tracking displays when divided attention is required to a cross-adaptive loading task," *Ergonomics*, vol. 16, no. 2, 1973, pp. 153–158, doi: 10.1080/00140137308924491.

[34] S. Gholinezhad, S. Dosen, and D. Jakob, "Electrotactile feedback outweighs natural feedback in sensory integration during control of grasp force," *J. Neural Eng.*, vol. 18, no. 5, Sep. 2021, Art. no. 056024, doi: 10.1088/1741-2552/AC1FCE.

[35] H. F. Seeley and J. C. Bliss, "Compensatory tracking with visual and tactile displays," *IEEE Trans. Hum. Factors Electron.*, vol. HFE-7, no. 2, pp. 84–90, Jun. 1966.

[36] I. D. Loram, H. Gollee, M. Lakie, and P. J. Gawthrop, "Human control of an inverted pendulum: Is continuous control necessary? Is intermittent control effective? Is intermittent control physiological?," *J. Physiol.*, vol. 589, no. Pt 2, pp. 307–324, Jan. 2011.

[37] C. E. Stepp, Q. An, and Y. Matsuoka, "Repeated training with augmentative vibrotactile feedback increases object manipulation performance," *PLoS One*, vol. 7, no. 2, 2012, Art. no. e32743, doi: 10.1371/journal.pone.0032743.

[38] F. Clemente, M. D'Alonzo, M. Controzzi, B. B. Edin, and C. Cipriani, "Non-invasive, temporally discrete feedback of object contact and release improves grasp control of closed-loop myoelectric transradial prostheses," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 24, no. 12, pp. 1314–1322, Dec. 2016.

[39] M. Štrbac *et al.*, "Short-and long-term learning of feedforward control of a myoelectric prosthesis with sensory feedback by amputees," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 11, pp. 2133–2145, Nov. 2017.

[40] J. Diedrichsen, R. Shadmehr, and R. B. Ivry, "The coordination of movement: Optimal feedback control and beyond," *Trends Cogn. Sci.*, vol. 14, no. 1. pp. 31–39, 2010.

[41] S. A. Daigle, R. E. Johnson, and J. W. Sensinger, "Effect of internal model development on effort and error during EMG control of three functional tracking tasks," in *Proc. 7th Int. IEEE/EMBS Conf. Neural Eng.*, 2015, pp. 703–706, doi: 10.1109/NER.2015.7146720.

[42] M. A. Garenfeld *et al.*, "A compact system for simultaneous stimulation and recording for closed-loop myoelectric control," *J. NeuroEng. Rehabil.*, vol. 18, no. 1, pp. 1–17, May 2021, doi: 10.1186/S12984-021-00877-5.

[43] D. Yang, Y. Gu, N. V. Thakor, and H. Liu, "Improving the functionality, robustness, and adaptability of myoelectric control for dexterous motion restoration," *Exp. Brain Res.*, vol. 237, no. 2. pp. 291–311, 2019, doi: 10.1007/s00221-018-5441-x.

[44] I. D. Loram, M. Lakie, and P. J. Gawthrop, "Visual control of stable and unstable loads: What is the feedback delay and extent of linear time-invariant control?," *J. Physiol.*, vol. 587, no. Pt 6, pp. 1343–1365, Mar. 2009.

[45] J. Tchimino, M. Markovic, J. Lund Dideriksen, and D. Strahinja, "The effect of calibration parameters on the control of a myoelectric hand prosthesis using EMG feedback," *J. Neural Eng.*, vol. 18, no. 4, 2021, Art. no. 34082406.

[46] T. R. Farrell and R. F. Weir, "The optimal controller delay for myoelectric prostheses," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 1, pp. 111–118, Mar. 2007.

Authorized licensed use limited to: Aalborg Universitetsbibliotek. Downloaded on March 14,2022 at 08:45:38 UTC from IEEE Xplore. Restrictions apply.