Haptic training

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Haptic training: Which types facilitate (re)learning of which motor task and for whom? Answers by a review

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***Abstract*—The use of robots has attracted researchers to design numerous haptic training methods to support motor learning. However, investigations of new methods yielded inconclusive results regarding their effectiveness to enhance learning due to the diversity of tasks, haptic designs, participants' skill level, and study protocols. In this review, we developed a taxonomy to identify generalizable findings out of publications on haptic training. In the taxonomy, we grouped the results of studies on healthy learners based on participants' skill level and tasks' characteristics. Our inspection of included studies revealed that: i) Performance-enhancing haptic methods were beneficial for novices, ii) Training with haptics was as effective as training with other feedback modalities, and iii) Performance-enhancing and performance-degrading haptic methods were useful for the learning of temporal and spatial aspects, respectively. We also observed that these findings are in line with results from robot-aided neurorehabilitation studies on patients. Our review suggests that haptic training can be effective to foster learning, especially when the information cannot be provided with other feedback modalities. We believe the findings from the taxonomy constitute a general guide, which can assist researchers when designing studies to investigate the effectiveness of haptics on learning different tasks.**

***Index Terms*—augmented haptic feedback, motor learning and neurorehabilitation, motor task classification, robot-assisted training, skill level, taxonomy**

I. INTRODUCTION

LEARNING and use of motor skills are crucial for humans to meet fundamental needs, interact with their surroundings, and perform activities of daily living independently [1], [2]. Thus, the topics of enhancing and optimizing motor skill acquisition (motor learning) and re-learning of lost functions (neurorehabilitation) have been extensively studied – see reviews in [3]–[5].

During motor (re-)learning, the availability of performance-related information is crucial to find a suitable action plan to enhance the quality of the learner's performance [6], [7]. In addition to the intrinsic information received from the sensorimotor system, i.e., "*the sensory, motor, and central integration and processing components involved in maintaining joint homeostasis during bodily movements*" [8], information on the learner's performance can also be provided from external sources in the form of instructions and feedback.

In recent decades, technological developments have stimulated the employment of technical instruments to provide external sensory information, e.g., visual, auditory, and haptic feedback, for promoting motor learning and neurorehabilitation [3], [4], [9]. In particular, the use of robotic devices has attracted researchers' interest to safely investigate the use of haptic feedback in motor learning and physically support patients with neurological disorders during intensive neurorehabilitation interventions without physically exhausting the therapists [3]. The generally employed paradigm is to physically guide the participants' limbs during movement training (haptic guidance). However, research in motor learning has stated that learners' effort and performance errors are crucial signals that drive motor learning [10], [11] and neuroplasticity [12]. Therefore, new haptic training methods have been proposed that make motor tasks more challenging, e.g., haptic disturbance [3], [13].

The effectiveness of haptic training methods has been investigated by an abundance of studies in the fields of motor learning and neurorehabilitation. However, these studies have driven inconclusive results, probably due to the diversity of the selected motor tasks, study protocol designs, investigated haptic methods, and the skill level of investigated participants groups. The identification of features that could influence the effectiveness of haptic feedback training on motor learning may facilitate the interpretation of current inconclusive results, which may provide generally applicable conclusions.

In this regard, Marchal-Crespo et al. previously proposed a taxonomy based on motor task characteristics and participants' skill level to identify potential haptic training strategies that enhance motor learning [14]. Their review of several own motor learning studies revealed that rhythmicity and duration

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of the movement to be learned, together with participants' initial skill level, play an important role in the effectiveness of robotic training methods. However, due to the limited number of compared studies and types of haptic methods included in their review, a categorical relationship between effective haptic training methods and specific motor tasks could not be found.

Several types of haptic methods were also reviewed by Williams and Carnahan in their comprehensive review [15]. However, their classification has neither considered recent efforts in the development of training methods that adapt during the training process nor new *hybrid haptic training methods* that merge different assisting or disturbing training strategies in a single method. Thus, in this review, we extended the taxonomy proposed in [14] by elaborating on the haptic feedback categorization presented in [15]. Overall, we aim to investigate the effectiveness of haptic methods on motor learning by:

i) Reviewing articles on robot-aided motor learning published in the last two decades,
ii) Distinguishing between performance metrics to be learned (e.g., spatial, temporal, and spatiotemporal),
iii) Extending the classification of motor task characteristics and haptic training methods.

II. Article Selection Criteria for the Taxonomy

In the taxonomy, we included motor learning studies that investigated the effectiveness of **augmented haptic training** methods – i.e., haptic information presented from external sources during task execution – on **healthy participants**. Findings from **robot-assisted motor learning** studies on healthy participants may provide relevant information to enhance re-learning of lost motor skills in neurologic patients, based on the assumption that motor learning and **neurorehabilitation** share the same brain mechanisms (i.e., neuroplasticity) [16], [17]. Therefore, studies with **neurologic patients** were also shortly discussed and their results were compared to motor learning findings with healthy participants.

We only included the studies, in which the experimental protocol included **short-term** or **long-term assessment** of motor learning after the training session. Only the studies that incorporated a **control group**, which practiced the motor task with a **robotic device**, either along with another feedback modality (visual, auditory) or without, were included to compare and discuss the benefits of the investigated haptic training methods over no-guidance (non-haptic) training. In terms of the inspected performance metrics, we focused on the kinematic features of the tasks, i.e., **spatial**, **temporal**, and **spatiotemporal** aspects.

The search query to find the articles with the aforementioned criteria was finalized in October 2020. We searched several academic databases (Google Scholar, IEEE Xplore®, PubMed) to select the articles, which were published after the year 2000. During the database search, we used multiple combinations and variations of the bold-formatted keywords in the previous two paragraphs. We also inspected previous articles that were referenced in relevant review articles in the field of motor learning [4], [9], [15], [18], [19] and neurorehabilitation [2], [3]. We included forty articles from the field of robot-assisted motor learning with healthy participants (included in the taxonomy) and nine articles from the field of neurorehabilitation with stroke patients.

III. General Conceptualities

In the following sub-sections, we provide an overview of the types of (haptic) feedback and haptic training methods found in literature to date and describe the characteristics of different learners' skill levels. We also provide a short description of types of (motor) performance assessment.

A. Types of (Haptic) Feedback and Haptic Training Methods

Feedback plays a crucial role in motor learning and motivation [20], [21]. In this review, we consider the term **feedback** as the information about the learner's performance [20] as a means of improvement. Feedback becomes available as a result of task execution and includes information about the difference between the learner's actual and desired target task performance, e.g., movement error. Feedback methods can be categorized in terms of the source of information (i.e., intrinsic vs. extrinsic/augmented), timing schedule (i.e., concurrent vs. terminal), and modality (e.g., visual, auditory, haptic, or combination of some of those) [4], [20]. Regarding the source, a feedback method is considered as **intrinsic** (inherent) if the information is perceived with the learner's natural sensory system – e.g., through proprioception and/or vision. In contrast, a feedback method is classified as **extrinsic** (augmented) if it is provided from sources outside of the learner's body, e.g., instructions from a coach or digital information on a screen. Concerning the timing schedule of feedback presentation, by definition, feedback is accessible after performing the task, which is referred to as **terminal feedback** [4]. Terminal feedback has been conventionally explored through the knowledge of results – i.e., information about the outcome of task performance – and through the knowledge of performance – i.e., information about the quality of performance [18], [21]. Thanks to recent years' technical development on computers' processing capabilities, both knowledge of results and knowledge of performance can also be provided in real-time during task execution, which is referred to as **concurrent feedback** [4].

Technological advancements allow researchers to investigate the effect of advanced feedback methods provided through visual, auditory, and haptic modalities, and their combinations (multimodal). In this review, we focus on the studies that investigated the effect of concurrent haptic feedback training on motor learning. We note that in the robot-aided motor learning literature, haptic training methods have also been presented along with other modalities, e.g., audiohaptic training [22], [23], visuohaptic training [24], [25], or audiovisuohaptic training [26]. For these types of multimodal training, the reader may refer to [4] for a review.

Haptic training methods can be categorized as performance-enhancing (haptic guidance) and performance-degrading (haptic disturbance) methods (Fig. 1), based on the

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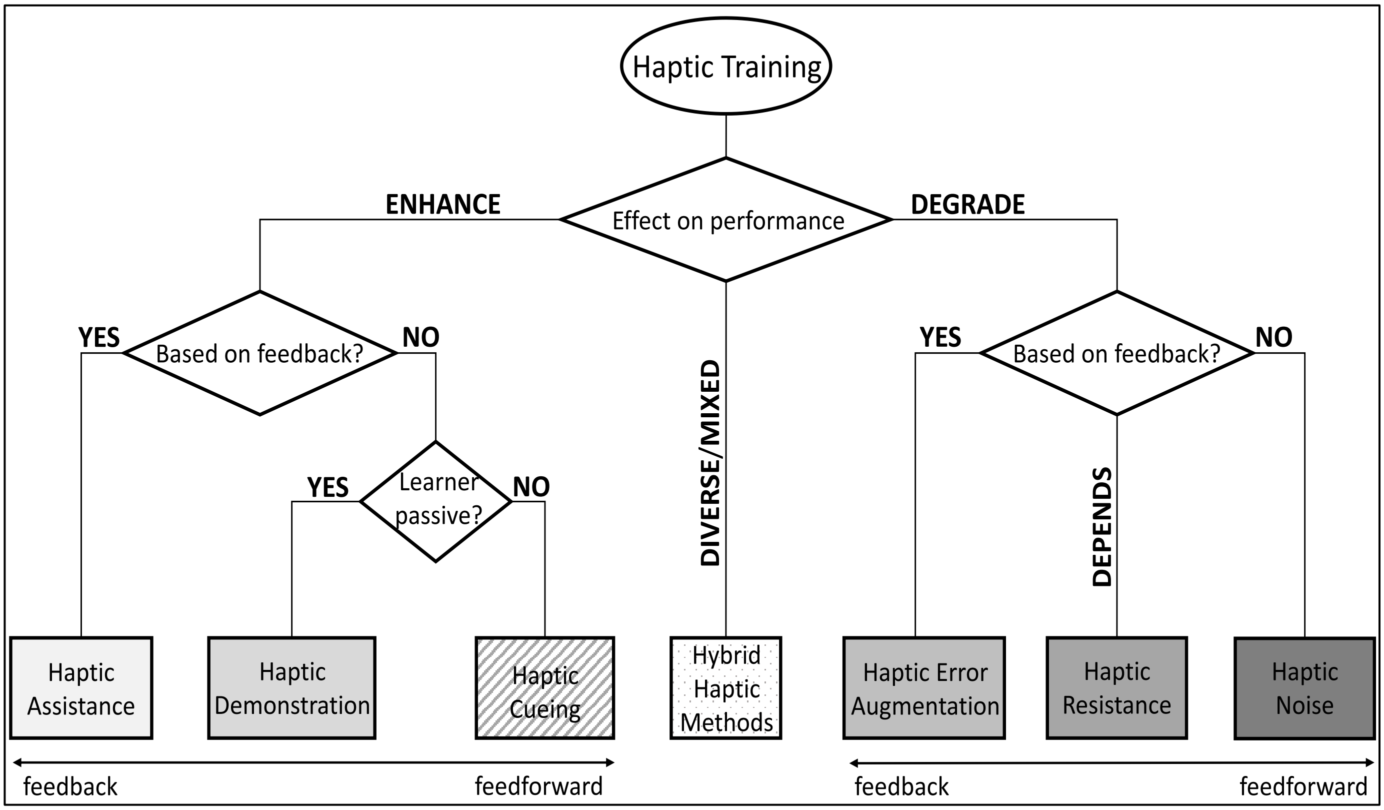

Fig. 1. Proposed classification of haptic training methods based on: i) the effect on the performance (enhancing vs. degrading), ii) the type of provided information (feedback vs. feedforward), and iii) activeness of the participants during training. Modified from [15]. A grey color scale from the lightest grey (haptic assistance) to darkest grey (haptic noise) was used to show decreased guidance/increased disturbance. The same color code was also used in the taxonomy shown in Fig. 3. In this review, haptic cueing was not included in the discussion of haptic methods; thus, the corresponding box was diagonally crossed.

effect of the haptic feedback on the learners' performance during training [15].

According to the classification proposed by Williams & Carnahan [15], **haptic guidance** encompasses the *haptic demonstration*, *haptic cueing,* and *haptic assistance* sub-methods. **Haptic demonstration** refers to the use of a haptic (robotic) device that displays the desired tasks' kinesthetic characteristics (e.g., spatial, temporal, and spatiotemporal aspects of motion) to the learner. During training with haptic demonstration, learners are fully guided by the haptic device and remain passive. In this review, **haptic cueing** is referred to as a vibrating-kind of tactile information or short pulses of forces to signal an upcoming movement, e.g., the correct moment to initiate a movement [27].

Among the three sub-methods under haptic guidance, **haptic assistance** is the only method that is characterized as feedback. As opposed to the haptic demonstration, during haptic assistance training, learners actively execute the motor task while they are guided/corrected by the haptic device. Haptic assistance methods can further be classified depending on the underlying robotic control design employed:

- *Proportional/Derivative controllers* that enforce the desired position/velocity of the limb [28]–[31],
- *Artificial potential field*s that restrict the movement to an area around the desired trajectory by correcting the movement with repulsive forces [1, 2], and/or to enforce a position-dependent velocity profile [3],
- *Haptic guidance in force* to enforce pre-recorded force profiles [32], [33],
- *Interactive controllers* that simulate the dynamics of a (human) partner on a robot, to which the user is haptically connected during task execution [34],
- *Entrainment* to match the frequency of a limb's motion with that of a robotic device [35],
- A combination of the above – e.g., path control and derivative control [36]–[38].

As opposed to haptic guidance, in which the haptic forces are applied to reduce the movement-related errors, **haptic disturbance** methods apply disturbing forces to exploit the assumption that errors drive motor learning [10], [39]. According to the haptic training classification proposed by Williams and Carnahan [15], haptic disturbance can be classified into:

- *Error augmentation*, in which forces proportional to the learners' movement errors push participants' away from the desired movement trajectory [13], [40], [41],
- *Haptic noise* that applies unexpected feedforward disturbing forces to increase movement variability [42], [43],
- *Haptic resistance* that uses opposing forces to the movement, which can be applied either dependent – e.g., reactive path control [44] – or independent on learners' performance [45].

In addition to the proposed haptic classification of Williams and Carnahan [15], we added the term *hybrid haptic training method* in the classification, which includes the haptic training

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methods that merge haptic guidance and disturbance in a single method – e.g., haptic assistance together with haptic noise [43], [46], and mixed controllers that amplify spatial errors and reduce timing errors [47].

The haptic training classification proposed by Williams and Carnahan [15] has some limitations. For example, their classification does not account for the haptic methods that modulate the guidance or disturbance during the training process (see Fig. 2 for a classification). **Fixed training** refers to a haptic training method, in which the controller parameters do not change during training [29], [48]. **Performance-based adaptive haptic training** refers to the haptic methods that adapt the controller's parameters – or assisting/disturbing forces – based on the online measurement of the learner's performance, either within a single training block [44] or within the overall study protocol [48], [49]. We employ the term **fading guidance** for the haptic training methods that systematically modulate the controller parameters as training progresses, independently of the learner's performance [24], [36], [50].

A second limitation of Williams and Carnahan [15] work, already stated by the authors, is that the proposed haptic classification does not capture how the haptic guiding forces can be provided without interfering with the haptic rendering of task-related elements, e.g., task dynamics [51]. Providing haptic guiding forces simultaneously to haptic rendering may create confusion [52], [53] and hamper motor learning [50], [54]. An initial body of research studied how haptic assisting forces can be separated from inherent task forces spatially – e.g., using different channels (end-effectors) –, or temporally – i.e., allocating time between the provision of training and task forces [53]. In our haptic classification we did not include the separation of the task and haptic guiding forces due to the limited number of studies on this topic.

B. *Skill Level*

Skill can be defined as the ability to perform a task "*with maximum certainty and minimum outlay of energy, or of time and energy*" [20], [55], which progresses as a result of task practice. The progress of skill acquisition has been proposed to follow three stages: a first cognitive stage (novice), a motor/associative stage (advanced), and a final autonomous stage (expert) [56].

During the cognitive stage, learners are challenged with an unknown task. Thus, **novice learners** usually rely on instructions and demonstrations to get familiar with the basic requirements of the task. During the cognitive stage, novices show a distinctive large improvement in their performance in a relatively short time. When a general understanding of the motor task has been reached, learners advance into the motor stage, in which they try to refine their actions to fulfill the task. Compared to the cognitive stage, **advanced learners** execute the task with higher precision and accuracy and more efficiency. Depending on the difficulty of the task, advanced learners generally spend more time in the motor stage and their performance improvement is less pronounced, compared to the cognitive stage. When the learners start developing automaticity in the execution of the motor task, they progress to the autonomous stage. At this stage, **experts** are usually close to the limits of their capabilities. Experts in the autonomous stage generally execute the task with the maximum precision and accuracy and minimum effort.

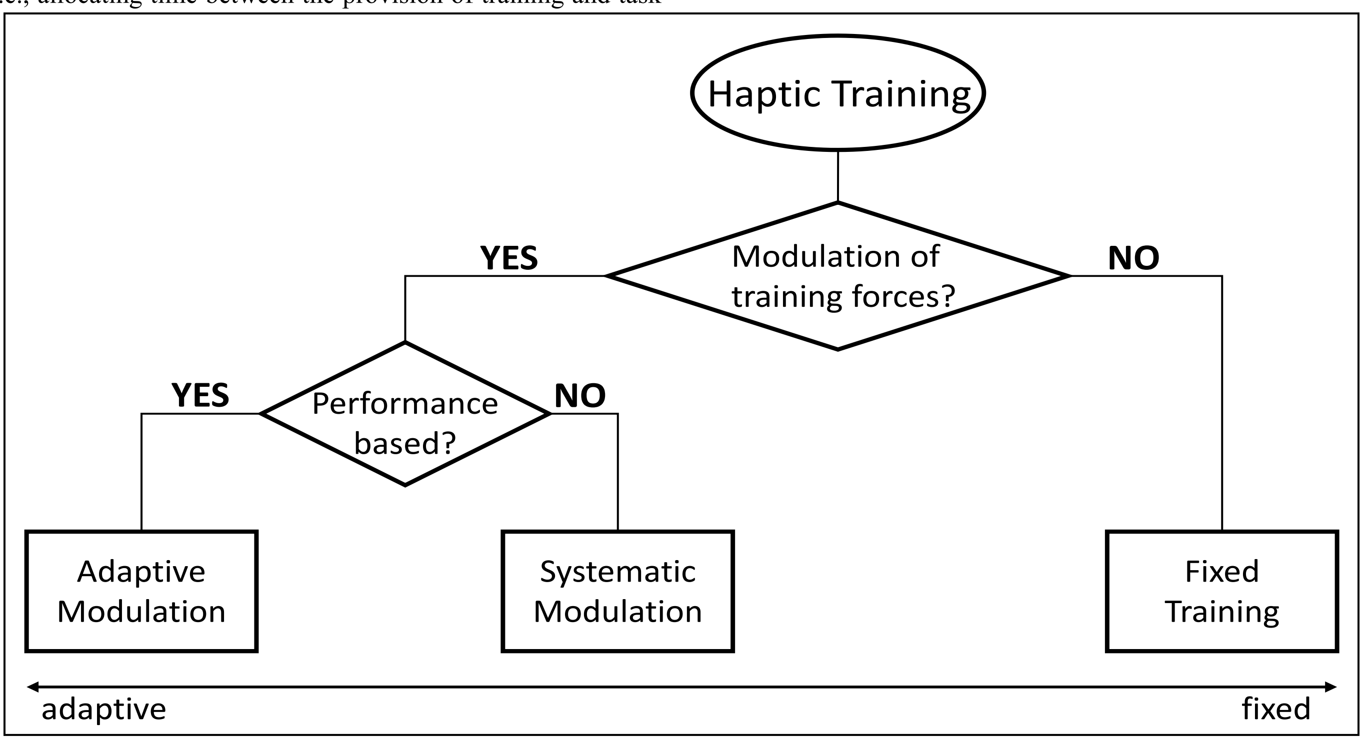

Fig. 2: Classification of the haptic methods according to the assistance/disturbance adaptation characteristics. Fixed training refers to non-adaptive haptic forces provided throughout the study protocol. Systematic modulation refers to the modulation of haptic training forces with a pre-selected scheme by the study designers. Adaptive modulation refers to the modulation of haptic training forces based on the participant's training performance. All three methods are applicable to any type of the haptic training methods presented in Fig. 1.

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According to the **challenge point framework**, the skill level of a learner plays an important role in the motor learning process [6]. The framework states that the motor task difficulty, along with the conditions under which the task is executed (e.g., a golf shot against various headwind conditions), should be matched to the learner's skill level to optimize learning. Importantly, the task difficulty can be modulated by robotic devices in terms of inherent task characteristics or haptic training methods, e.g., changing the simulated water density in a rowing task [57] or haptically assisting/challenging the learners [44], [58].

The majority of studies on robot-aided motor learning have been conducted with novice learners during the cognitive stage (e.g., [30], [47]). The number of studies on advanced learners is, however, scarce (e.g., [42], [58]). To our knowledge, no studies have evaluated the effectiveness of robot-aided haptic training methods on experts in the autonomous stage.

C. Types of Performance Assessment

The repeated assessment of performance during the training process allows the evaluation of the participants' learning progress. In this review, we adopt the term **motor performance** as the performance during training, when learners execute the motor task under the support of augmented feedback. Thus, the motor performance does not reflect the genuine success of the learners, since their real performance might be masked by the provided augmented feedback.

The learner's absolute success on a motor task must be assessed when the augmented feedback is not present. Motor learning studies incorporate various types of assessment tests in their protocol – e.g., *baseline* tests to evaluate learners' performance before training starts, *recall* (catch) tests embedded within training sessions where the augmented feedback is removed, and *retention* tests performed after the training is finished [15]. We refer to **motor learning** as the progress in learner's absolute success in the motor task as a result of training (i.e., the performance change between baseline and retention tests) [59], [60].

Motor learning is distinguished from motor performance in that the skill is assessed without any augmented feedback and the elapsed time between training and assessment allows for the memory consolidation of acquired skill [61], [62]. In motor learning studies, retention tests that are conducted at least 24 hours after training are recommended to assess long-term motor learning [15], [18] and eliminate the temporary effects of haptic training on the performance – e.g., slacking on the guiding forces [59]. When learning is assessed with a retention test right after the final training session or with a recall test conducted after every training run, we use the term s*hort-term motor learning*.

Finally, we use the term **generalization** to refer to the ability to transfer the gained skill from the practiced nominal motor task to a novel, unpracticed or altered version of the nominal motor task, e.g., writing a different letter than those trained. Generalization is assessed through transfer retention tests, which are administered after training sessions. To assess the improvement in the transfer task after training, a baseline transfer test is needed before the training starts.

IV. Proposed Taxonomy

In this review, we propose a taxonomy (see Fig. 3), which builds on the one proposed by Marchal-Crespo et al., in [14]. We classified the investigated motor tasks based on the involvement of discrete and continuous movements, and single vs. rhythmic/repetitive task execution – i.e., discrete single, discrete repetitive, continuous single, and continuous rhythmic (see *Motor Task Characteristics* for the description of terminologies). We extended the classification by considering the task (spatial) complexity (simple: 1 DoF, complex: 2+DoF) and the investigated movement aspects (spatial, temporal, and spatiotemporal aspects). Furthermore, we distinguished the outcomes from the robot-aided training studies according to the time of assessment of motor learning (short- vs. long-term retention). Lastly, although specified by only a few reviewed studies [30], [31], [42], [47], [58], the presented taxonomy also informs the reader regarding whether the participants' initial skill level was statistically considered when reporting the effectiveness of the haptic training strategies on motor learning.

In the following two sub-sections, the terms used in the organization of our proposed taxonomy are presented.

A. Performance (Outcome) Metrics

The success in the task execution can be quantified with designated performance metrics. Performance metrics allow the assessment of learning by evaluating the created **spatial** errors (e.g., deviation to reference path) [53], **temporal** errors (e.g., movement time) [63], **spatiotemporal** errors (e.g., velocity error, smoothness) [25], [32], and error variability (e.g., standard deviation of errors) [30], [64]. Different types of haptic feedback might have contrasting effects on these movement aspects. For example, several studies have shown a benefit of haptic guidance in learning to reproduce the temporal, but not the spatial, characteristics of complex spatiotemporal curves [28], [65]. Thus, in this review, the effectiveness of the investigated haptic training methods is discussed separately for spatial, temporal, and spatiotemporal performance metrics.

Physical and mental effort have been proposed as important outcome metrics in motor learning experiments [60]. Less physical and mental effort is related to the notion of automaticity in the final autonomous stage of motor learning [56], [60]. However, we did not include effort as an outcome metric in our review because only a limited number of studies have measured effort either objectively (e.g., using electromyography [58], or brain activation [42]), or subjectively (e.g., using questionnaires [30]), probably because the number of studies on advanced and expert learners is scarce.

B. Motor Task Characteristics

The specific characteristics of the motor task to be learned might play an important role in the effectiveness of robotic training [14], [47], [53]. In our taxonomy we have considered different task characteristics (i.e., complexity, continuity, and rhythmicity) to systematically evaluate the role of task elements on the effectiveness of different haptic training methods.

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1) Complexity

In motor learning literature, the term **task complexity** has been mainly associated with the difficulty of executing or mastering the task [9]. Several researchers have attempted to define task complexity through various performance metrics (e.g., movement time, reaction time, spatial or temporal error and variability) or task's characteristics (e.g., degrees of freedom, task's constraints, redundancy, and limb coordination [9], [66]).

In line with the complexity definition by Wulf and Shea [66], we consider the motor tasks that require one degree of freedom (DoF) – either in joint space or in end-effector/task space – as spatially simple tasks. Motor tasks that incorporate two and more DoFs were regarded as spatially complex tasks. In this bounded, yet measurable definition of complexity, if the task success was assessed based on an end-effector movement, we considered the DoF in task space (e.g., 1 DoF for turning a steering wheel). If the success was assessed based on the learner's limb posture or joint movements (e.g., the posture of the arms during steering wheel turning), then the motor task was classified based on the DoF in the joint space (e.g., use of two or more arm joints).

2) Continuity and rhythmicity

Based on their own experimental results, Marchal-Crespo et al. [14] proposed a classification taxonomy – an extension of the motor task organization introduced by Schmidt and Wrisberg [20] – to categorize tasks depending on their continuity (discrete vs. continuous) and rhythmicity (single execution vs. rhythmic).

A **discrete task** is defined as a momentary action that has clear beginning and end poses whereas a **continuous task** is defined as a relatively long-lasting movement that does not possess a clear beginning and end [20]. Golf putting and drawing are two examples of such task categories, respectively. Motor tasks that incorporate **single task** execution, e.g., hitting a ball with a tennis racket or pressing a key, and **rhythmic/repetitive** motions, e.g., rowing or walking, have been shown to be related to distinct control primitives/actions [67] and involve distinct brain circuitries [68]. Based on such findings, haptic methods that support learning of single motor tasks might not be suitable to also support the learning of rhythmic movements; thus, these types of motor tasks were evaluated independently.

V. Results and Discussion

Based on the comparison of findings that fall into the same category in the taxonomy, we aimed to propose effective haptic methods that depend on the specific task characteristics. We identified generalizable patterns regarding the effectiveness of haptic training methods on the investigated performance metrics. Moreover, we found that the design of the haptic training methods has contrasting effects on the retention of different performance metrics. Therefore, the discussion of the reviewed studies was structured based on the type of inspected performance metrics and the design of the haptic training methods.

In the next section, we discuss general findings from all the reviewed studies regarding the effectiveness of haptic training methods for the learning of spatial, temporal, and spatiotemporal aspects of motor tasks from the perspective of the challenge point framework [6], and compare the benefit of haptic methods with other training modalities such as visual and auditory feedback. Findings from robotic rehabilitation studies on stroke patients are also presented and their analogy to the findings from motor learning studies is outlined.

A. General Findings

1) Haptic training: Its effectiveness explained by the challenge point framework

We observed a general pattern regarding the efficacy of haptic training on motor learning, which aligns with the statements of the challenge point framework [6]. We found that the effectiveness of haptic training depends on the:

i. Inherent challenge presented by the task (nominal task difficulty),
ii. Amount of task-relevant information conveyed by the haptic training method (conditional task difficulty),
iii. Initial skill level of the learner (functional task difficulty).

Nominal task difficulty can be viewed as the challenge due to the incorporation of spatial [33], [69], temporal [31], [35], and spatiotemporal [30], [44] requirements that are inherent to the execution of a task. The provision of haptic guidance or disturbance during training may further modulate the challenge presented to the learner, i.e., **conditional task difficulty**. Finally, the initial skill level of the learner modulates the **functional task difficulty**, i.e., how challenging the execution of the task is perceived by a specific learner during training.

Concerning the motor learning of simple motor tasks, we observed that the learners' skill level was generally adequate for overcoming the task challenges; thus, the modulation of the conditional task difficulty by means of haptic training did not additionally contribute to motor learning [43], [49], [50], [58], [70]. When learning complex motor tasks, training with haptic methods was generally more effective in comparison to no-guidance training [32], [36], [40], but as effective as concurrent visual feedback [31], [44], [46], [54] and at best as effective as terminal feedback [27], [41], [63], [71]. Thus, for a general pool of healthy learners, the availability of other training modalities (visual and auditory) might as well promote the learning of complex tasks due to the provision of task-relevant information. Nevertheless, the employment of haptic training might be effective in the absence of other feedback modalities and in case learners are too weak to perform the task by themselves, e.g., brain-injured patients.

Regarding the impact of the learners' skill level on motor learning, performance-enhancing training methods were observed to promote motor learning in initially less skilled participants [30], [31], [47], [72] and children [24], [37], [73], [74]. Although there is an initial body of evidence that supports the idea that performance-degrading haptic methods might benefit learning in initially more skilled learners [42], [72], this conclusion still needs further validation as only a limited number of studies has inspected the effect of skill on the effectiveness of performance-degrading haptic methods.

Complexity	Training Method	Discrete						Continuous					
		Single			Repetitive			Single			Rhythmic		
		Spatial	Sp.temp.	Temporal	Spatial	Sp.temp.	Temporal	Spatial	Sp.temp.	Temporal	Spatial	Sp.temp.	Temporal
1 DoF	H. Asst.		[30^{N}]	[35, 70]	[47^{N}, 50]	[50]		[47,43,49]		[49,48, 43]	[58,50]	[50]	[35]
	H. Demo.						[22,23]						
	H. Err. Augm.		[30]								[58]		
	H. Res.										[44]		
	H. Noise.							[43]		[43]	[58]		
	Other			[27^{N},35]	[47^{v}]	[22]	[22,23]	[47^{v}, 43,69]		[43]			[35]
2+ DoF	H. Asst.						[29, 29]	[74,28,32,33, 53,41,63,71]	[32,74, 28,31,63]	[31,63,71]	[44^{N}, 44,27]	[27^{N}, 53,44,75]	[27^{N}, 29]
	H. Demo.										[44]	[44]	
	H. Err. Augm.	[40,64]	[40,64]	[64]				[71, 41,63]	[63]	[63,71]	[42^{S}, 42^{N}]		[42]
	H. Res.										[44]	[44^{N}]	
	H. Noise.							[41,36, 53,54]	[54]		[42^{S}, 42^{N},54]	[53,54]	[42]
	Other		[38]	[31^{S},31^{N}]	[23]		[23]	[37,36,73,54, 69,79,105]	[24, 31,26,54]	[37, 31,26,105]	[25^{N},27,$46^{S,v}$,54]	[25^{N},27,$46^{S,v}$,54,76]	[27]

Fig. 3: Proposed taxonomy. The grey scale of the cells refers to the type of haptic feedbacks illustrated in Fig. 1. The "Other" row refers to all haptic training methods, which are multimodal and/or hybrid type of haptic methods. Reviewed studies were represented with their respective reference numbers. Green and blue colors refer to the statistically significant superiority of a training method (compared to the control group) in delayed and immediate retention/transfer tests, respectively. Red and orange colors refer to insignificant differences in delayed and immediate tests, respectively. Superscripts "*N*", "*S*" refer to the results for *Novice* (initially less skilled) participants, and (initially) *Skilled* participants, respectively. Superscript "*v*" refers to the fact that our assessments were also based on the visual inspection of the presented graphs in the corresponding papers. For the detailed description of study designs and results, refer to Table S.II in the supplementary material. For the detailed explanation of abbreviations used in Fig. 3 and Table S.II, refer to Table S.I.

In the next subsections, common findings regarding the efficacy of performance-enhancing and performance-degrading haptic feedback on the learning of spatial, temporal, and spatiotemporal aspects of tasks are presented considering the learners' initial skill level and availability of information.

2) Performance-enhancing haptic training: Effective for initially less skilled learners

a) Spatial aspects

Haptic guidance seems to be beneficial for initially less skilled participants on the long-term learning of spatial aspects, as shown on a simple discrete reaching task with haptic assistance [47] and a complex continuous rowing task with adaptive path control [44]. Although no significant differences were found among the compared groups in the delayed retention tests of either study, the groups that received haptic guidance started with poorer spatial performance in baseline compared to the other groups and were the only training groups that could significantly reduce the spatial error [44], [47] and error variability [47] at transfer [47] and retention tests [44].

These findings are further supported by the studies conducted with children. In a trajectory following task [73], the error reduction after training with visuohaptic guidance was significantly greater than in the visual feedback group. Similarly, in a line-following task with a pediatric powered wheelchair [74], the adaptive haptic assistance was effective in significantly reducing the tracking error from baseline to the immediate retention test in a significantly greater amount than training without guidance. In a similar driving study [37], toddlers who received a combined haptic assistance method (path and position control) significantly reduced the spatial error at the delayed retention test and reached significantly lower error values in the transfer test compared to the no-guided control group.

The complexity of the task to be learned also seems to play a crucial role in the effectiveness of performance-enhancing haptic methods. Several studies have shown that haptic guidance is not an effective training strategy to promote the learning of spatial aspects of simple motor tasks [43], [49], [50], [58]. In [50], neither the fixed nor the fading training haptic methods could outperform no-guidance training in terms of spatial error reduction in the delayed retention test of a **simple and rhythmic** virtual ball-bouncing task. Similar results were found when training a simple and rhythmic gait-like movement performed with haptic guidance [58] and a **simple and continuous** task, i.e., steering a vehicle on straight roads [43], [49].

Haptic guidance was also found to be ineffective for the learning of spatial aspects in a priori more complex tasks, such as a 2-DoF letter-writing task [33]. In [33], training with 'haptic guidance in force' and haptic guidance based on position control did not result in better learning than the no-guidance group. Although the writing task in [33] is spatially complex, and therefore, based on the challenge point framework, a benefit of haptic guidance could have been expected, the general writing skills of adult participants probably made the task rather trivial.

Taken together, initially less skilled participants seem to benefit from performance-enhancing haptic methods to learn the spatial aspects of the task, probably because the conditional task difficulty is reduced, and learners are optimally challenged. However, in especially simple tasks, the imposed task difficulty might be already within the skill capabilities of the participant, and therefore, performance-enhancing haptic methods would further reduce the challenge from its optimal point and hamper learning.

b) Temporal aspects

Performance-enhancing haptic methods were found beneficial to learn temporal aspects, compared to no-guidance training, as shown on several driving/steering tasks [43], [48], [49]. In a virtual driving task with a non-holonomic vehicle [48], training with fixed and adaptive haptic guidance resulted in significantly better steering performance in the retention test than training without guidance. The authors showed in a follow-up study [49] that training with haptic guidance helped participants to find the optimal timing to initiate turns and straighten the vehicle direction when coming out of turns. The long-term effectiveness of adaptive haptic guidance and hybrid haptic guidance (a weighted combination of assistance and disturbance) on learning the steering tasks' timing aspect was also observed in [43].

The effectiveness of the performance-enhancing haptic methods on learning temporal aspects is especially evident in initially less skilled participants [27], [31], [37]. In [31], training with fading haptic guidance reduced the timing error in a complex tennis task significantly more than training with visual feedback for the initially less skilled participants in the short term. Similarly, when learning a complex rowing task in [27], only the haptic guidance group, who showed a poorer baseline performance compared to the other groups, significantly reduced the timing error in the long term. Overall, the results from the studies on the tennis and rowing tasks, in which the timing of sub-tasks (e.g., hitting the ball, rotating the oar) are crucial for the success of the main task, indicate that haptic guidance might be useful for the learning of timing aspects of complex movements in initially less skilled learners.

c) Spatiotemporal aspects

Performance-enhancing haptic methods were also found to be effective for initially less skilled learners to enhance the spatiotemporal performance in the long term [27], [30]. On a simple golf putting task, participants with poorer baseline performance were observed to significantly reduce the spatiotemporal variability after training with haptic assistance compared to training without guidance [30]. On a complex rowing task [27], only the haptic guidance group, which started with the poorest baseline performance, significantly reduced the spatiotemporal errors at the delayed test.

Children were also observed to benefit from the support of haptic guidance to improve their spatiotemporal performance. In a pediatric power wheelchair steering task [74], the fading haptic assistance group increased the wheelchair speed significantly more than the no-guidance group in the immediate retention test. Similarly, in a letter-writing task [24], the fading visuohaptic assistance group performed significantly better than the no-guidance group in the delayed test for all spatiotemporal metrics related to the smoothness of handwriting. The results observed in children in training hand-writing tasks contradict those observed in adults. For example, on the letter-writing task in [32], the position control type of haptic guidance did not result in a significantly better spatiotemporal performance than no-guidance training. A possible rationale is that adults have already developed an automatic and proactive control of handwriting movements, while children may still depend on the sensory feedback due to a lack of formal handwriting training. Thus, haptic guidance seems to provide a suitable training environment for learners who lack initial knowledge of the spatiotemporal aspects of complex movements.

When the learners' initial skill level is not taken into consideration, performance-enhancing haptic methods do not seem to provide any additional benefit over practicing the task without haptics for the learning of spatiotemporal aspects of motor tasks [28], [38], [50], [53], [75], [76]. For example, in a series of experiments that investigated the effect of different types of haptic guidance methods on learning a virtual hitting task with a joystick, the performance-enhancing haptic methods did not enhance the learning of spatiotemporal aspects [53], [75], [76]. Several factors might have contributed to the overall ineffectiveness of the haptic guidance methods when compared to training without guidance. The relatively low nominal and conditional task difficulty imposed on the participants probably did not challenge the participants to achieve better performance. Indeed, the authors found that the ideal movement that yields the most hit counts might be a simple 1-DoF continuous rhythmic movement instead of a planar movement. In addition to the low nominal task difficulty and task complexity, the availability of visual information during training – i.e., participants could see how accurate they were in reaching the hitting targets – might have been sufficient to successfully hit the targets. Thus, haptic feedback probably stayed redundant for motor learning [77]. Importantly, since the guidance was constantly provided without adaptation, participants may have relied on the haptic feedback and failed to gain the required skills, which is in line with the guidance hypothesis [59], [78].

One study found positive effects of fixed haptic guidance over no guidance in learning the spatiotemporal aspects in a circle drawing task that incorporated a desired elliptic velocity profile [28]. The fixed haptic guidance group reduced the error significantly more than the control group in the velocity amplitude metric. However, this significance might have resulted from the fact that the control group's performance deteriorated after training.

Contrary to the observed inefficacy of haptic guidance methods on learning the spatiotemporal aspects of tasks, the 'haptic guidance in force' method – i.e., haptic assistance to enforce pre-recorded force profiles – was found to enhance the learning of spatiotemporal metrics related to the smoothness of movement in short-term assessments conducted on two motor tasks, i.e., drawing letters and ellipses [32]. The authors discussed that the relevant spatiotemporal aspect of the movement – e.g., the velocity profile – might have been better conveyed with the force coordinates, instead of the spatial coordinates as encoded in position guidance. Despite the promising benefit of haptic guidance in force on motor learning, to our knowledge, no other studies have explored the benefits of this haptic method on learning the spatiotemporal aspects of more complex tasks.

3) *Performance-degrading haptic training: Beneficial when learning spatial aspects and in initially more skilled learners*

Performance-degrading haptic methods, through increased participants' effort and attention, might provide a close-to-optimal challenge to moderately skilled participants. Thereby, the individual motor learning process is better supported, compared to no-guidance training and performance-enhancing methods [30], [42].

a) Spatial aspects

Performance-degrading haptic training was found to be effective for learning the spatial aspects of various simple and complex tasks [36], [40], [41], [46], [47], [64], [71].

On a **discrete** point-to-point motion task, the error augmentation group significantly reduced the movement variability from baseline to the immediate retention test [64]. Likewise, on another reaching task on a horizontal plane, an error-field haptic method helped to reduce the spatial error significantly more than no-guidance from baseline to the immediate-retention test (see [40], the application of error augmentation forces was only provided in parts of the movement where the participants were prone to deviate more often from the desired trajectory). Contrary, on a **simple continuous** tracking task, researchers found that hybrid haptic feedback did not result in better learning compared to training with visual feedback and fixed haptic guidance (see [47], the hybrid haptic feedback combined error augmentation when errors are small with haptic guidance when errors become larger than a threshold).

We also found evidence of superior learning associated with training with performance-degrading haptic methods in more **complex** tasks. In [41], the results from the delayed retention tests on a 2D shape-contour tracking task showed that the haptic noise group attained the lowest tracking error, with marginal statistical significance, compared to the visual feedback group. In similar complex continuous tasks – e.g., letter-writing [71] and line tracing tasks [63] – training with error augmentation significantly reduced the spatial error from baseline to the delayed retention, although differences with the no-guidance group did not reach significance. Finally, on a joystick steering task, training with haptic disturbance reduced the spatial error in the short-term significantly more than the no-guidance group [36].

Performance-degrading methods are especially beneficial for initially more skilled participants [42], [58]. On a **complex rhythmic** stepping task [42], the short-term retention test revealed that initially more skilled participants benefited from the performance-degrading haptic methods, while initially less skilled participants benefited more from training without haptic guidance group. Therefore, in line with the challenge point framework, learners who were initially more skilled required a higher challenge to promote learning, which was provided by the performance-degrading haptic method. Nevertheless, the results from the short-term assessment need to be corroborated by long-term assessments.

A potential rationale behind the observed benefit of performance-degrading haptic methods on learning the spatial aspects of the motor task may be explained by the increased active participation of learners during the task execution. This explanation is supported by the stronger muscle activation observed during training with haptic error augmentation and haptic disturbance methods, compared to haptic guidance and no guidance, during a stepping-like task [58]. However, it is also important to note that training spatial aspects with performance-degrading haptic methods has been shown to have a negative effect on participants' motivation [30], [42], and could potentially hamper motor learning if they increase participants' frustration during training.

b) Temporal aspects

Performance-degrading haptic methods were not found to be effective for the learning of temporal aspects of **complex discrete** – e.g., a point-to-point reaching task executed in 3D space [64] – **complex continuous** – e.g., letter-writing task [71], or curve tracing task [63] – and **complex rhythmic** tasks – e.g., stepping task [42].

The inefficacy of the performance-degrading haptic strategies might be attributed to their design, as they generally incorporate the essential spatial information (e.g., deviation from the desired trajectory) but not temporal information of the motor tasks. Other performance-degrading haptic strategies that do not only rely on the spatial errors in their design, such as haptic resistance, might be better candidates to enhance the learning of temporal aspects of motor tasks.

c) Spatiotemporal aspects

We did not find any studies regarding the effect of performance-degrading haptic methods on learning tasks' spatiotemporal aspects for moderately skilled participants. For a general pool of participants, in one study, training with adaptive haptic error augmentation supported learning of spatiotemporal aspects [45], while in another study the benefit of error augmentation over training without haptics could not be shown [25]. However, such inconsistent results were mainly due to the design of the performance-degrading haptic methods and the feedback provided to the control group in non-haptic modalities. Finally, we would like to note an important observation: performance-degrading methods were found to be ineffective to learn spatial aspects when the task incorporated velocity constraints [25], [44], [54].

On two distinct tracking tasks with desired velocity profiles [54], the haptic disturbance group hampered learning of spatial aspects, probably because participants were excessively challenged by the performance-degrading feedbacks in terms of learning spatial errors on top of spatiotemporal aspects. The resistance type of haptic training methods was also observed to be ineffective for learning tasks' spatial aspects on top of velocity requirements in a complex rowing movement [25], [44]. A possible explanation for the poor effectiveness of the resistive haptic training method might be that its presence disturbed the smooth task execution, especially in the initially poor-performing participants who constantly deviated from the desired trajectory [25]. Indeed, although the resistive haptic feedback was designed to increase the awareness of spatial errors, the correcting forces may have constantly interrupted participants and prevented them from focusing on learning the correct velocity profile. Thus, although performance-degrading haptic methods were found to increase awareness of errors and support the learning of spatial aspects in motor tasks [46], [47], [71] when the desired velocity information is missing in the haptic design, learners might be confused, hampering learning.

4) Haptic training: Equally effective to visual, auditory, and terminal feedback

The overall findings from the reviewed studies suggest that haptic training methods are as effective as other feedback modalities like visual, auditory, and terminal feedback) in terms of supporting the learning of spatial, temporal, and spatiotemporal aspects of motor tasks. Nevertheless, in the absence of any other type of augmented feedback about task requirements and performance, haptic training can be an effective tool to support motor (re-)learning. In comparison to other modalities, haptic training can be especially effective for situations in which making errors can be dangerous or demotivating, e.g., initially less skilled learners and stroke patients.

Within the next subsections, we report results from studies that compared haptic methods with visual, audiovisual, auditory modalities, and terminal feedback on learning the spatial, temporal, and spatiotemporal aspects of motor tasks.

a) Haptic vs. visual feedback

Several studies have shown that haptic training can be as effective as visual feedback to learn the spatial [25], [44], [47], [69], [79], temporal [31], [35], and spatiotemporal [31], [44], [46], [54], [63], [64] aspects of motor tasks.

On a complex continuous 2D shape drawing task, both the visuohaptic guidance and visual feedback groups could significantly lower the **spatial** deviation errors from the first test to the final delayed retention test [79]. However, no significant differences were found between training methods. Similar results were observed in a path following task [69]. Further, in [47] no significant differences were found between training with haptic assistance, visual feedback, and hybrid haptic feedback (error augmentation and assistance when needed) on learning spatial aspects of simple continuous tracking and discrete reaching tasks.

On a simple task of lever-rolling to propel a wheelchair, both the haptic guidance – based on the resonance entrainment principle – and visual feedback groups significantly reduced the **temporal** error from baseline to long-term retention and transfer tests [35]. Although the visual group's long-term performance was closer to the target frequency, no significant difference was observed between the visual and haptic groups. Also, on a complex tennis task, which required tracking two distinct slow and fast desired velocity profiles, training with haptic guidance and visual feedback did not yield any significant reduction of the overall **temporal** and **spatiotemporal** error at the immediate retention test [31]. Moreover, no significant differences were found between groups in the retention test.

Performance-degrading haptic methods yielded inconsistent results when training **spatiotemporal** aspects compared to

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visual feedback. Hybrid haptic error augmentation was compared to visual feedback and visual error augmentation in training an asymmetric walking task [46]. Although the hybrid haptic error augmentation group reached the highest spatiotemporal performance in the delayed retention test, no significant differences in terms of error reduction were observed among groups. Contrary, on a point-to-point reaching task, haptic error augmentation was found to significantly improve the spatiotemporal aspects in the immediate retention test, when compared to visual feedback [64]. Similarly, in [44] only the reactive path controller training group could significantly reduce the mean velocity error in a rowing task in the long term compared to the visual feedback, haptic demonstration, and adaptive path control groups. However, the observed significance may be related to the poorer baseline performance observed in the reactive path control group.

Taken together, the general finding that haptic feedback could not outperform visual feedback for the learning of spatial and temporal aspects might be attributed to the fact that the visual information may have already been sufficient [80], [81], which was also observed in [57]. Thus, the information provided by the haptic feedback methods during training did not further contribute to skill progress.

b) Haptic vs. audiovisual and auditory feedback

In general, haptic methods were found to be as equally beneficial as audiovisual and auditory feedback in learning spatial [25], temporal [22], [23], [26], [29], and better than auditory feedback in learning spatiotemporal aspects of motor tasks [22].

Training with audiovisual feedback did not result in better learning of **spatial** aspects in a complex rowing task [25] compared to concurrent visual feedback and concurrent visual feedback combined with a reactive path controller. Thus, concurrent visual feedback was already effective for learning the task and the addition of audio and haptic feedback on top of visual feedback did not provide further information to enhance learning. In the same study, resistive haptic training did not yield a significant improvement in the **spatiotemporal** aspects of the complex rowing task. In the delayed retention test, the velocity performance of the visuohaptic group was significantly worse than the audiovisual feedback group, which in turn resulted in a slightly better average velocity performance than the concurrent visual feedback group.

Similar results were observed in the learning of **temporal** aspects. In a complex shape drawing task with bimanual coordination, in which passive audiovisuohaptic (haptic demonstration in addition to visual and auditory feedback) and audiovisual active training methods were compared [26], no differences between groups in terms of temporal and spatiotemporal error reduction were found. In two distinct studies conducted on audio-motor tasks, training with haptic demonstration benefitted the reduction of temporal errors as much as **auditory demonstration** – i.e., playback of the sounds– and audiohaptic demonstration (percussion learning: [22]; key pressing: [23]). Lastly, training with haptic guidance supported learning of the relative temporal error on an intermittent circle drawing but not on a continuous circle drawing. However, training with haptic guidance did not yield significantly superior performance in the recall tests compared to auditory demonstration training regarding the absolute timing aspect in both drawing tasks [29].

Importantly, in a study that analyzed learning of a percussion task [22], the authors found that training with audiohaptic demonstration, compared to only haptic demonstration, and only audio demonstration methods, significantly improved the **spatiotemporal** performance. The rationale behind the fact that the addition of haptic demonstration to audio information could outperform audio demonstration for the spatiotemporal aspect, i.e., velocity, but not for the temporal aspect is that the velocity is a more complex feature of the task compared to timing. Thus, the addition of haptic demonstration may have added relevant information to enhance the spatiotemporal performance.

c) Haptic vs. terminal feedback

In general, haptic methods were found to be as equally beneficial as terminal feedback in learning spatial [63], temporal [27], [63], [71], and spatiotemporal aspects of motor tasks [30], [63].

On a complex line tracing task, the effectiveness of the haptic error augmentation on learning **spatial** aspects was marginal in comparison to the visual and terminal feedback group [63]. Further, no significant group differences were found between the fixed haptic guidance and the no-guidance groups in the **temporal** aspects. A possible explanation is that all groups received terminal feedback, i.e., knowledge of performance and results after the training. It is an open question whether the effectiveness of the haptic error augmentation might have been more pronounced if the groups had not received such additional relevant information.

On a simple button-pressing task in a pinball-like virtual game, no significant differences in terms of the reduction of the timing errors from baseline to retention were found between the adaptive haptic guidance and the control group receiving knowledge of performance and results [70]. Similarly, on a complex rowing task, no significant differences in the **temporal** error (duration of a rowing stroke) were observed in the delayed retention tests between the group receiving position control and vibrotactile feedback and the terminal feedback group [27]. On a writing task, neither the fixed haptic guidance (virtual fixture) nor the knowledge of results group could significantly improve their temporal performance (task completion time) from baseline to the delayed retention tests [71]. The comparative effectiveness of the haptic methods to the no-guided groups might be attributed to the fact that participants in both studies were already provided with a set of task-relevant information regarding the task completion time and deviation after the training.

B. Robot-aided Neurorehabilitation with Stroke Patients: Findings in Line with Those from Motor Learning Experiments

1) Performance-degrading haptic training: Effective for relearning spatial aspects

In general, haptic error augmentation methods were found to be more effective than conventional repetitive training (e.g., [13], [82], [83]) and haptic guidance methods (e.g., [13], [84], [85]) for re-learning motor tasks' **spatial** aspects in stroke patients. Haptic guidance, on the other hand, did not provide

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any additional benefit compared to conventional repetitive training [86], [87].

Error augmentation was shown to promote a more active control of the arm compared to standard repetitive training and haptic guidance [83], [85]. As discussed in [13], [82], [83], neurological patients trained with haptic error amplification are compelled to explore new motor strategies to successfully execute the desired task as opposed to haptic guidance training, which generally restricts patients' movement to a predefined trajectory/pattern. Further, amplifying errors may enhance the signal-to-noise ratio for the sensory feedback and allow the impaired nervous system to react to movement errors that are normally difficult to notice [13]. Finally, training with error amplification enhances patients' effort during training [58], [88], crucial to improve the paretic limb's strength [89] and drive neuroplasticity [12]. On the contrary, haptic guidance compels patients to rely on the assistance, resulting in slacking effects [90] and a reduction of energy expenditure [91]. Thus, the lack of additional benefit of the haptic guidance over conventional, manual repetitive training might be attributed to the fixed nature of the implemented haptic guidance, which did not take into account the patients' progress throughout the training intervention [86]. An adaptive haptic training tailored to patients' needs, might be a better approach to enhance recovery [92].

2) Performance-enhancing haptic training: More effective than performance-degrading training for relearning temporal aspects

After a thorough search in the robotic neurorehabilitation literature, we only found a study that evaluated the effect of training with haptic methods on learning tasks' temporal aspects in stroke patients [93]. The authors compared the effects of haptic guidance and error amplification on learning a simple discrete task in a pinball-like game. They found that only the haptic guidance group could significantly reduce the temporal error in the short term to a significantly greater extent than the error amplification group. Importantly, the location of the brain lesion played a role in the (in)effectiveness of the haptic methods, i.e., training with error augmentation was especially detrimental for left hemispheric stroke patients, while no effect of brain lesion location was observed in the haptic guidance group. Further studies with a more heterogeneous patient population and with a broader span of motor impairment are needed to confirm whether the haptic guidance is indeed superior to error amplification and standard repetitive training in the long term.

3) Haptic training: May not always outperform standard (repetitive) training for relearning spatiotemporal aspects

In line with the results from the motor learning studies with healthy participants, neurorehabilitation literature suggests that although error augmentation and haptic guidance might support re-learning of tasks' spatiotemporal aspects in moderately to severely impaired chronic stroke patients in the long term [84]–[86], [94], these haptic methods do not seem to outperform conventional repetitive task training.

We propose two reasons that might be behind this outcome. First, the lack of additional benefit of haptic training on the spatiotemporal aspects, as opposed to learning the spatial aspects, might be explained by how well stroke patients can cope with increased muscle tone – i.e., spasticity, loss of inhibition of motor neurons that causes excessive velocity-dependent muscle contraction – and proprioception loss [95], [96]. Spasticity is directly linked to the movement speed [13], [97], while proprioception significantly contributes to the perception of spatiotemporal information [98]. Although spasticity and proprioception decline might negatively limit spatial performance, patients could still rely on their visual perception to gather spatial information [80], [81]. Second, none of the investigated haptic paradigms incorporated an adaptive design based on patients' impairment level, and therefore, participants were probably far from their optimal challenge point. As stated by the guidance hypothesis, motor learning can be hindered if the participants rely on the guidance forces since the required muscle activation may not be correctly developed [59].

VI. Considerations for Future Work

In this section, we first propose future research directions for haptic training that takes into consideration the amount of task-relevant information provided, participants' skill level, and selection of performance metrics. Finally, we conclude by providing guidelines to enhance the design of future motor learning studies.

A. Derived Future Research Directions

1) The role of the learners' skill level on the effectiveness of robotic training highlights the need for performance-based (adaptive) haptic training methods

As stated by the challenge point framework, motor learning can be optimally supported when the provided challenge matches with the skill progression of the learner [6]. Robotic training offers a unique opportunity to adapt the conditional task difficulty to the specific learners' skill level. Modulating the guiding or disturbing forces depending on the learner's performance may be the most effective training strategy to optimally support the overall skill acquisition.

An initial body of research focused on designing haptic training methods that could adjust the task difficulty to meet the individual needs of learners with different skill levels, e.g., haptic guidance [99], haptic disturbance [30], and adaptive/selective robotic training strategies (e.g., automatic selection of feedback methods [100]. However, to date, adaptive methods have not been extensively investigated in motor learning studies [40], [49]. Among the few studies that assessed adaptive haptic training, adaptive designs have been mostly applied on performance-enhancing methods (e.g., [38], [43], [44], [58], [75]), and rarely on performance-degrading haptic methods (e.g., [40]).

Because the majority of the reviewed haptic training methods were applied with a non-adaptive scheme, participants in these haptic training groups, especially in long-term studies, may have not received the most optimal task challenge to enhance motor learning. In such a scenario, if the participants were deprived of an adequate challenge based on their improved skills, a boredom effect might have also arisen. Therefore, to keep the participants motivated, prevent slacking on the guidance forces, and provide them with the most optimal challenge along the study protocol, investigation of adaptive haptic training designs should be prioritized in comparison to non-adaptive methods.

2) The design of the haptic feedback training methods should ensure that task-relevant information is properly delivered

Haptic feedback can be realized using diverse methods/controllers that can affect motor learning differently (for a complete list of haptics methods, please refer to the *Types of (Haptic) Feedback and Haptic Training Methods* section). From the reviewed literature, we observed that haptic feedback strategies might hamper motor learning when the feedback:

i. Does not provide task-relevant information,
ii. Is difficult to interpret/use by the participants,
iii. Changes the participant's perception of the main goal of the task.

Depending on the design of the haptic feedback method, the task characteristics can be unintentionally altered. For example, on a rhythmic lever manipulation task to propel a wheelchair, participants in the haptic guidance group consistently executed the arm movements with larger amplitudes than the visual group [35], which led to a larger deviation from the target optimal frequency. Since the movement amplitude was not constrained for any group, when the haptic feedback was applied, participants may have not judged well enough whether their movement amplitude would be suitable to result in the target frequency of the movement. This issue might have been solved by clearly defining the task execution constraints by incorporating relevant task information – e.g., the actual amplitude of arm movement – in the design of the haptic method.

Another common issue associated with the design of certain haptic training methods is that they are difficult to interpret/use by some participants [53], [54]. For example, in [53] authors evaluated a new haptic method that separates the haptic assisting forces from inherent task forces (i.e., a spring-damper dynamic system) spatially – i.e., using different channels (end-effectors) –, or temporally – i.e., allocating time between the provision of training and task forces. The authors attributed the observed ineffectiveness of these novel methods and participants' self-reported high frustration levels to the difficulty to interpret the feedback designs. Further, the novel designs may have led participants to focus on task-irrelevant aspects, such as trying to interpret the received information during training. A possible solution to minimize this potential problem would be to allow participants to familiarize with the newly proposed haptic feedback designs before training starts.

Finally, the design of the haptic method may alter the learners' perception of the task's goals and they may adopt undesired strategies during training. In such cases, participants may not benefit from the conveyed information as intended. For example, in [41] authors attributed the lack of efficacy of error amplification training over visual feedback to the predictability of the repulsive forces. During training, the error amplification group was constantly pushed to the opposite direction of the movement, resulting in participants' conforming to the poor performance, instead of trying to overcome the challenge. This problem may be mitigated by designing haptic methods with clear and reachable task goals.

3) Robotic neurorehabilitation could benefit from the knowledge gained in motor learning studies

In motor learning studies, various types of haptic guidance methods were observed to be beneficial for the initially less skilled participants on the learning of spatial [47], temporal [27], [31], and spatiotemporal [30] aspects of motor tasks. In the neurorehabilitation field, researchers also found that initially more severely impaired stroke patients benefited more from performance-enhancing haptic methods, and in some cases, from haptic error augmentation, while less impaired patients only benefited from error augmentation (e.g., [84], [85]). Although both the haptic guidance and error amplification methods used in [84] and [85] need to be compared to standard repetitive task practice for the validation of their findings, it might be possible that performance-enhancing haptic methods help severely impaired patients to experience new somatosensory information [86] to enhance neuroplasticity while performance-degrading haptic methods help patients to detect the performance errors that would not usually be noticed by the sensory system [101].

The reviewed motor learning literature suggests that haptic noise and resistive haptic training might be beneficial for the learning of tasks' spatial aspects [36], [42], [58]. However, to our knowledge, the effectiveness of haptic noise and haptic resistive methods have not been assessed in stroke patients. Nevertheless, haptic noise and resistive haptic training strategies might have great potential to also increase patients' attention and motor learning due to increased performance errors.

In motor learning literature, haptic training methods were generally found to be as effective as the compared terminal and concurrent visual feedback training methods to drive motor learning in healthy participants [27], [35], [63]. Haptic training is an excellent training method in neurorehabilitation, as it helps diminishing spasticity [86], and reduces dangerous and frustrating errors [102]. Nevertheless, although stroke patients may not benefit from the provision of visual/auditory feedback training methods alone due to muscle weakness, the provision of visual/auditory and terminal feedback in addition to haptic methods may enhance the effectiveness of the overall training by providing a more enriched multisensory information to patients [103].

As a final note, according to [104], the list of preferred skills by stroke patients to be trained during rehabilitation interventions consists of both, continuous tasks – e.g., writing and steering a wheel – and discrete tasks – e.g., using a keyboard. However, based on our taxonomy, the majority of studies with healthy participants focused on the learning of continuous tasks, whereas discrete tasks have been comparatively less explored. On the contrary, most of the upper-limb neurorehabilitation studies focused on discrete tasks, e.g., planar reaching. Therefore, motor learning and neurorehabilitation communities are encouraged to investigate the effectiveness of haptic training methods in both continuous and discrete tasks, to gain a better understanding of the neuroplasticity process that underlines both, motor learning and neurorehabilitation.

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B. General Guidelines for the Use of Haptic Methods in Prospective Motor Learning Studies

The reviewed studies differed in several factors such as study protocol design, performance metric selection, and feedback design. Therefore, deducing meaningful inferences was not always straightforward. Based on the gathered information, in this section, we provide guidelines to improve the design of future motor learning studies.

1) Designing an equitable control group is essential to drive conclusions

Control groups are used as baseline strategies against which other haptic feedback methods are compared. For a fair assessment of the effectiveness of the haptic training methods on learning, the design of the control group should ensure, at least, the following features:

i. Training the same nominal motor task with the robotic device as the other haptic groups,
ii. The provision of task-relevant (ideally non-haptic) information to enhance participants' motivation and learning.

In the context of haptic training, the nominal task to be learned should not be regarded as the task per se – e.g., writing with a pen – but rather the execution of the task with a robotic apparatus – e.g., writing with the stylus pen of a Phantom device – since the use of the apparatus may modify the nominal task's kinematics and dynamics, e.g., due to robot's inertia and friction [105]. Thus, if the control group trains without the robotic device, the trained task might be nominally different than the one trained by the haptic-practice groups. In that case, if motor learning is assessed with the robotic apparatus in the retention tests, the tested task would become a transfer task condition in the control group, rather than a retention task [65], [106]–[108].

The provision of task-related information to the control group is crucial for enhancing the motivation of learners [109] and plays a crucial role in the effectiveness of the investigated training strategies. In this review, the previously employed term 'no-guidance' referred to those training methods that did not incorporate haptics. However, we note that the majority of those studies incorporated some kind of task-relevant information during training. Nevertheless, we found some studies that did not provide any kind of information to the control group during training (see Table S.II in Supplementary Material). This imposes an important problem, as the lack of performance-related information may reduce participants' motivation to comply with the training, especially in multi-day and long-term studies, and does not provide any supporting means to drive motor learning [57]. In such a scenario, the differences between the haptic feedback group and the control group might be disproportionately pronounced in favor of the haptic method [36], [40], [49].

2) A familiarization phase is needed to precisely assess skill acquisition

In motor learning, the nonlinear relationship between training and performance suggests that a higher amount of training is required to attain small performance improvements as the skill level progresses [110]. This typical learning exponential curve was observed in the performance improvement of post-stroke participants who trained a reaching task with the assistance of a robotic device [111]. Importantly, stroke patients exhibited a fast and a slow improvement curve. The authors attributed the first fast improvement phase to the familiarization to use the new robotic device and virtual reality visualization, and the slow phase to motor recovery, highlighting the importance of distinguishing the resultant motor (re-)learning from the familiarization phase. However, the inclusion of a familiarization phase prior to baseline or training session has been only seldom reported in the reviewed studies [26], [33], [35], [38], [41], [46], [58], [63], [64], [70], [76].

In studies that did not include a familiarization period, the reported improvements in the performance metrics from baseline to retention might have been confounded with the amount of participant's gradual habituation to the use of the robotic device, instead of the actual motor learning of the desired aspect of the motor task. Besides, potential performance improvements from baseline to retention tests done with a robotic apparatus in a control group that does not train with the robotic device may be due to the familiarization of participants in the use of the device, rather than reflect learning of the nominal task. Therefore, the addition of a familiarization phase to get used to the robot in no haptic guidance mode is crucial when designing robot-aided motor learning protocols to precisely assess the learners' baseline performance as well as their performance's improvement after training.

3) Controlling for the effect of differences in learners' initial skill level on motor learning

The assessment of the learners' baseline performance is important to determine participants' initial skill level and evaluate the extent of motor learning – i.e., performance improvement from baseline to retention tests. Importantly, the learners' initial skill level has been shown to play an important role in the effectiveness of different haptic methods [13], [42], [72], [84], [94], [112].

To prevent that random allocation of participants into different training groups results in differences in baseline performance between groups that might bias results, three design features have been implemented in the literature:

i. Using a pre-training test to determine the skill level of participants, and using adaptive randomization methods to allocate new participants in different groups based on their initial skill level, as in [42], [49],
ii. Providing all groups with the same intervention procedure until all participants attain a similar performance level, as in [113],
iii. Incorporating the initial baseline performance as a dependent variable in the statistical analysis, as in [30], [31], [42], [58].

The first and second features usually guarantee a fair baseline distribution among the groups, at the expense of reducing the 'naïveté' of participants towards the investigated motor task [57]. If such a side effect is not desired, the third plan might yield an unbiased comparison among the tested groups.

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4) The correct selection of the performance metrics is crucial to evaluate learning of the temporal, spatial, and spatiotemporal aspects of the task

The selection of the performance metrics had a direct impact on the reported effectiveness of the haptic training methods on motor learning. Three observations associated with the metric selection should be considered in future studies:

i. The selected performance metric should be suitable to reflect the learning progress of the specific task,
ii. The selected metric should not be sensitive to uncontrolled participant's behavior during training,
iii. Improvements on metrics selected to evaluate one specific task aspect may be confounded by the learning of another task's aspect.

Performance metrics should be selected before the motor learning study starts based on previous literature or knowledge of the task to be learned. However, some selected performance metrics based on well-educated guesses might be unsuitable to measure motor learning. For example, in a study that evaluated learning of a ball-bouncing task [50], authors employed the racquet acceleration at ball impact as a spatiotemporal performance measure, based on previous studies that suggested that to correctly bounce a ball to a desired apex, the racquet-ball collision should happen when the racquet is deaccelerating [114]. However, in [50] none of the training methods (including no guidance) resulted in a significant spatiotemporal error reduction after training, neither a correlation between task performance and deacceleration at impact was found. The authors attributed the ineffectiveness of all the training schemes to the unfitness of the selected spatiotemporal performance metric. Thus, researchers are recommended to test the suitability of the selected performance metrics in pilot tests prior to the main motor learning study.

Participant's uncontrolled behavior during training might also play an important role in motor learning results. For example, in [28], the slight benefit of haptic guidance over visual feedback on learning the maximum and minimum speed of a velocity profile on a tracking task might be explained by the unforeseen behavior of participants in the control group. As the authors discussed, participants in the visual group sped up at certain points of the trajectory when they saw they lagged behind the desired position, and this velocity correction might have resulted in higher speed peaks compared to those in the desired velocity profile. Thus, performance metrics should be chosen such that they are not sensitive to participants' uncontrolled behavior during training.

Finally, changes in one performance metric might be cofounded by changes on a different metric. For example, in [36] authors reported that haptic guidance was beneficial for the learning of spatial aspects of a steering task. However, it is unclear whether the observed spatial performance improvement could be attributed to the reported effectiveness of haptic guidance on learning the correct time to initiate turns (i.e., temporal aspect) that resulted in smaller tracking errors in [43], [48], [74]. Thus, the selected spatial metric – i.e., deviation from the path – in [36], [105] might have also captured the enhanced time performance during turns. Thus, researchers are encouraged to evaluate the possible confounding effects of different performance metrics during data analysis.

5) Long-term and transfer tests are needed to assess motor learning

Motor learning is a product of experience and training that leads to a relatively permanent change in the learners' skills. Many studies in this review only assessed short-term learning with recall (catch) tests, which were interspersed among training sessions [22], [23], [28], [53], or with immediate-retention tests right after the training [29], [31], [42], [48], [54]. However, since the haptic intervention may have immediate and short-lived influences on learners' performance, e.g., slacking on the guiding forces [15], [59], a delayed-retention test administered at least 24 hours after training should be employed to accurately evaluate motor learning.

Another condition of motor learning is to be able to apply the learned motor skills in a new similar task, also called motor skill transfer [60]. However, only a handful of studies in the presented literature administered long-term transfer tests on an altered version of the trained tasks [35], [47], [63], [70], and only one study assessed the generalization of robotically trained skills in a real-life task [46]. Therefore, in future studies, researchers are encouraged to conduct long-term transfer tests, along with the delayed retention tests, for a thorough investigation of the effectiveness of haptic training methods.

6) Motor learning should be evaluated with both, between-group learning differences and within-group progress of performance

In the majority of the reviewed studies, the effectiveness of haptic methods was either reported from the evaluation of within-group changes of performance from baseline to retention – i.e., did training result in motor learning? (e.g., [30], [40], [47], [54]) – or between-group differences in retention tests – i.e., did training with different training methods result in differences in the final performance? (e.g., [23], [38], [41], [43]). However, only a few studies reported both the within-group performance changes and the difference between the groups in the final attained performance values (e.g., [25], [27]). Reporting only the group differences in retention tests may not allow for interpreting the particular benefit of the investigated haptic training on learning. Reporting the performance change after training with a percentage change may yield misleading results, especially if the group differences in the baseline are not accounted for [115]. Thus, in line with the recommendations from Schmidt and Lee [60], to make meaningful comparisons among the investigated training methods, both results from the within- and between-group statistical analysis should be reported.

VII. General Conclusion

Based on the reviewed studies, four *features* that influence the effectiveness of haptic training methods on motor learning were determined:

i. The skill level of learners (novice, advanced, and expert),
ii. The feedback design (performance-enhancing and performance-degrading, adaptive and non-adaptive feedback),
iii. The outcome of motor learning (spatial, temporal, and spatiotemporal aspects),

iv. The motor task characteristics (complexity, continuity, and rhythmicity).

The comparison of the studies in the proposed taxonomy confirmed that the effectiveness of haptic training could be explained by the statements of the challenge point framework [6]. More specifically, the effectiveness of a haptic training was found to be dependent on the nominal task difficulty (e.g., motor task characteristics and required aspects of the motor task to be learned), the conditional task difficulty (e.g., the design of the haptic training method), and the functional task difficulty (e.g., the learner's skill level). Therefore, any interpretation concerning the effectiveness of haptic training methods on motor learning is subject to the interaction of the identified features.

Haptic training methods were generally beneficial for promoting motor (re-)learning. Firstly, performance-enhancing haptic training methods were found to be effective for novice learners on the learning of spatial, temporal, and spatiotemporal aspects of motor tasks, while performance-degrading haptic methods benefited initially more skilled participants in terms of learning spatial aspects. Secondly, for a general pool of participants/learners, haptic training was found to be as effective as training with other non-haptic modalities for learning different motor tasks. Thus, in the absence of any other type of feedback or in tasks where errors can be dangerous or frustrating, haptic training can be an effective tool to support motor learning. Finally, regarding the learning of specific aspects of motor tasks, performance-enhancing and degrading methods were generally found to be effective for learning the temporal and spatial aspects, respectively. When considering functional task difficulty, findings from motor learning studies with healthy participants are in line with results from neurorehabilitation experiments with stroke patients. This insight could be employed to improve current robotic-aided neurorehabilitation paradigms.

Overall, the collection of the presented findings establishes a reference guide for the researchers in the field of robot-aided motor learning to select and design appropriate haptic training methods depending on the participants' skill level and characteristics of the motor tasks to be learned.

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