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# Enabling human–robot teaming through haptic feedback: From caged automation to collaborative interaction

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ABSTRACT

Robotic systems have progressed from fenced industrial automation to co-located collaboration and, more recently, AI-mediated human–robot teaming. Haptic feedback provides a physical channel for intent communication, contact regulation, and safe interaction in close proximity. This structured narrative (scoping-style) mini-review focuses primarily on force-mediated and physically grounded haptic interaction – including impedance/admittance control, force exchange, contact regulation, and shared-control mechanisms – while discussing tactile, cutaneous, and vibrotactile modalities where they complement, localise, or communicate those interactions. It organises the field by addressing: (RQ1) how haptic modalities and devices evolve across interaction stages; (RQ2) which control and stability/safety strategies are used and what trade-offs they impose; and (RQ3) how performance is evaluated and what remains missing for reproducible comparison. Literature was identified through a structured scoping-style search and screening process across IEEE Xplore, Scopus, Web of Science, and Google Scholar (2000–2025); 63 key sources were retained for the final synthesis after duplicate removal, relevance screening, and backward/forward reference snowballing.For analytical clarity, we organise prior work into five interaction modes:caged robots (isolated industrial automation), human–robot interaction (HRI) including teleoperation and command-oriented haptic cues, shared-workspace human–robot collaboration (HRC), physical HRC (pHRC) with bidirectional force exchange, and AI-supported human–robot teaming (HRT). For each interaction mode, we distinguish between intentionally delivered haptic cues to the human (e.g., kinesthetic, tactile, cutaneous, or vibrotactile feedback), forces physically experienced during co-manipulation or incidental contact, and the robot-side sensing/compliance-control mechanisms (e.g., force/torque sensing and impedance/admittance) that shape or regulate those interactions, alongside the relevant safety constraints and commonly reported metrics (stability, transparency, workload, task efficiency, and safety). The main synthesis output is a design-space matrix that maps each interaction mode to the dominant haptic purpose, what the human mainly feels, robot-side enablers, primary design priorities, and typical evaluation focus/main risks. A single unified comparative modelling subsection, rather than four stage-specific derivations, supports this matrix by presenting the compact Equation (1)–Equation (11) progression only as an interpretive abstraction. Open problems include stable high-fidelity haptics under delay and uncertainty, reproducible benchmarking, and safety guidance for AI-adaptive haptic cues in teaming scenarios.

## 1. Introduction

Robots are increasingly deployed in environments where they share space, tools, and sometimes physical contact with humans. In these settings, haptic feedback provides a direct and intuitive communication channel, complementing vision and audio, by conveying contact forces, constraints, and interaction intent. Across interaction modes ranging from physical separation to close-proximity cooperation and teaming, the role of haptics shifts from improving teleoperation *transparency*, that is, how faithfully the operator perceives the remote environment and robot dynamics through the interface, to enabling compliant physical collaboration and, more recently, supporting coordination and intent communication in shared-autonomy settings [1,2].

Despite substantial progress in human–robot systems, the role of haptic feedback is still not consistently translated into deployable design guidance. This is partly because the evidence base is distributed across communities that often use different assumptions and

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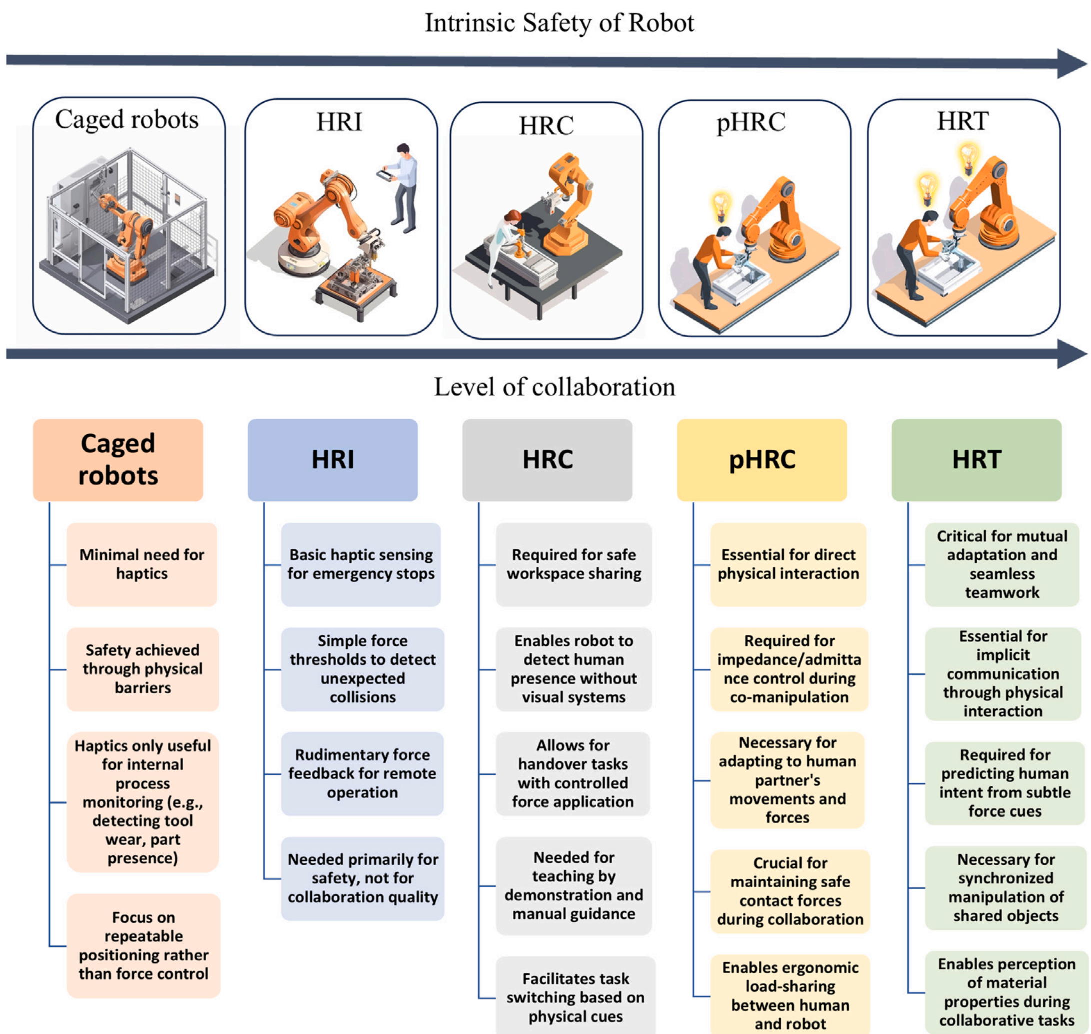


**Fig. 1.** Five interaction modes used in this review as an analytical lens for comparing how the role of haptic feedback changes across different forms of human–robot integration [3].

evaluation practices (e.g., teleoperation transparency and delay robustness, collaborative-robot (cobot) safety and compliance in shared workspaces, and AI-mediated shared autonomy and teaming). As robots increasingly operate in close proximity to people, haptics becomes a practical requirement for communicating contact state, intent, and confidence–yet it also introduces stability, calibration, and safety challenges that are not addressed uniformly across the literature. This motivates a concise, haptics-centric synthesis that compares the interaction modes through explicit design and evaluation dimensions, complemented later in the paper by a design-space matrix for practical interpretation.

To keep the Introduction focused on motivation, we use the five categories in Fig. 1 as an analytical lens: distinct interaction modes or dominant operating configurations that help compare how the role of haptic feedback changes under different assumptions about proximity, physical coupling, and authority sharing. They are not intended as a strict historical ladder, nor do we treat their definitions as overlapping. Rather, depending on the application scenario, systems may move fluidly between these modes or emphasise different modes at different phases of operation. In this sense, caged automation is treated mainly as a baseline reference case, while HRT is discussed as a higher-level coordination layer that may be realised in different interaction settings. Table 1 summarises how the role of haptic feedback changes across the interaction modes.

This paper is a structured narrative (scoping-style) mini-review rather than a full PRISMA-ScR systematic review [4]. The aim is to synthesise key themes and design implications through a transparent but proportionate review procedure, rather than to provide an exhaustive systematic mapping of the field. Literature was identified through keyword searches in IEEE Xplore, Scopus, Web of Science, and Google Scholar over the period 2000–2025. To improve traceability, Section 2 now summarises the search scope, representative keyword logic, screening workflow, duplicate handling, screening criteria used to focus the retained set, and stage-wise grouping used to retain the final set of sources. The synthesis is then organised using the five-category analytical lens in Fig. 1, with consistent extraction across stages of (i) the role of haptic feedback, (ii) typical enabling technologies/devices, (iii) modelling/control choices, and (iv) distinctive unresolved challenges.

A distinction that is important throughout this review is between *human-perceived haptics*, *physical interaction forces*, and *robot-side sensing/control*. What the human actually feels may arise through: (i) intentionally delivered cues through kinesthetic, tactile, cutaneous, or vibrotactile channels; (ii) forces physically experienced during co-manipulation or incidental contact, which may be informative without necessarily being designed as explicit feedback; and/or (iii) interaction shaping by robot-side mechanisms such as force/torque sensing, joint-torque estimation, contact detection, and impedance/admittance

**Table 1**
Comparison of Haptic Feedback Across the interaction modes Considered in This Review.

| Stage | Haptic feedback role | Interaction characteristics |
|---|---|---|
| Caged robots | Minimal or no haptic feedback | Isolation, no direct human interaction |
| HRI | Enhances command-based interactions | Limited physical contact, teleoperation, improved precision |
| HRC | Force feedback ensuring safe coexistence | Shared workspace (*coexistence*/light *cooperation*); collaborative tasks; safety-critical incidental contact |
| pHRC | Bidirectional force exchange for cooperation | Sustained physical coupling (*cooperation*); co-manipulation/load sharing; real-time bidirectional force exchange |
| HRT | Adaptive AI-driven teaming feedback | Autonomous teaming, intent interpretation, proactive adjustments |

control. In scope terms, the primary emphasis of this review is on force-mediated and physically grounded haptics, that is, interaction shaped by compliance, force exchange, contact regulation, and shared control across HRI, HRC, pHRC, and HRT. Tactile, cutaneous, and vibrotactile channels remain part of the discussion where they complement or localise these interaction states, but the manuscript is not intended as a standalone exhaustive review of tactile display design [5–9].

In the broader HRI/HRC literature, particularly in industrial contexts, interaction levels are often described using terms such as *co-existence* and *cooperation*. For example, in [10] authors discuss these concepts as practical degrees of human–robot interaction in manufacturing. In our framework, *coexistence* maps most directly to **HRC** (shared workspace with predominantly incidental contact, where haptic/force feedback supports contact detection, compliant response, and standards-driven safety constraints). *Cooperation* spans **HRC** and becomes most explicit in **pHRC**, where the human and robot share loads through sustained physical coupling and bidirectional force exchange (e.g., co-manipulation and hand-guidance). This mapping preserves established terminology while keeping the focus of this review on how haptic feedback changes across interaction paradigms.

In line with this distinction, the five categories are treated in this review as analytically distinct interaction modes rather than as a quasi-evolutionary ladder. The intention is not to claim that their definitions overlap, but to acknowledge that real systems may move between modes depending on the application scenario, task phase, degree of physical coupling, and allocation of human/robot authority [9–13]. Caged automation is retained as a baseline reference case, whereas HRT is discussed as a coordination layer that may be realised in different interaction settings.

Existing reviews typically focus on individual parts of the problem, such as teleoperation/surgical haptics, industrial HRC safety and interfaces, admittance control for physical interaction, or AI shared autonomy and intent inference, often using different assumptions and evaluation conventions [7,9,11,12,14]. In contrast, this mini-review provides a force-mediated, haptics-centric synthesis across caged automation, HRI, HRC, pHRC, and HRT, with the design-space matrix in Table 7 serving as the main output for comparing dominant haptic purpose, felt interaction, robot-side enablers, design priorities, and evaluation risks across the interaction modes.

In addition to the database-driven screening, we refined the stage taxonomy and prioritised the practical gaps through informal consultations with domain experts in haptics and collaborative robotics (primarily academic researchers engaged through our knowledge-exchange activities). These discussions reinforced three recurring insights: (i) the need for reproducible benchmarks that jointly report task performance, interaction forces, and human factors; (ii) the centrality of standards-driven force/pressure limits, and their limitations for sustained physical coupling; and (iii) the importance of designing AI-adaptive haptic cues that are legible and non-coercive to reduce mode confusion and preserve trust in teaming. These inputs were used to refine the synthesis, terminology, and comparative presentation, but they do not constitute a formal expert-elicitation study.

From a literature perspective, the most mature body of work sits in *HRI*, where haptic rendering and bilateral teleoperation have been extensively studied in contact-rich domains (notably surgical teleoperation and hazardous/remote manipulation), with a strong focus on transparency, stability under delay/uncertainty, and controlled user-study metrics [2,5,14–16]. The most widely cited quantitative synthesis in this space remains the older teleoperation-focused meta-analysis of Nitsch and Färber, which reported a large overall task-performance effect (Hedges' $g = 0.96$, 95% CI 0.71–1.21) but also substantial heterogeneity ($Q = 92.75$, $I^2 = 66.6\%$), so its findings should be interpreted as indicative rather than uniformly generalisable across all HRI tasks [16]. A second highly investigated area is *industrial HRC*, where force feedback is frequently discussed through the lens of safe shared-workspace operation, compliance, and measurable reductions in peak interaction forces and collisions; here, the design space is more directly shaped by collaborative-robot safety guidance (e.g., ISO/TS 15066 body-region-specific force/pressure limits for quasi-static and transient contact) [9,17–19]. In *pHRC*, the literature is growing but comparatively less standardised: sustained physical coupling (co-manipulation of bulky objects and rehabilitation-style assistance/resistance exercises) makes comfort, ergonomics, and variable human impedance central, and outcomes depend strongly on admittance/impedance tuning and safety enforcement beyond simple force limits [11,20,21]. Finally, *HRT* is the least mature from both a standards and benchmarking standpoint: shared autonomy and intent inference are well studied, but the use of haptics as an intent/confidence communication channel (and the implications of AI-adaptive gain scheduling on "feel", stability, and user trust) remains an emerging area with limited stage-specific standard guidance and fewer reproducible evaluation protocols [7,12,13,22]. Table 2 summarises which stages and interaction phases are currently most prevalent in the literature and where standards most directly constrain haptic design.

Nevertheless, designing effective haptic feedback systems presents ongoing challenges. The feedback must be meaningful and intuitive, requiring a deep understanding of human perception, cognition, and task-specific needs. Stability and transparency in haptic interactions, particularly under communication delays or dynamic uncertainties, demand sophisticated control strategies, such as input-to-state stability (ISS) or time-domain passivity approaches [23,24]. The interdisciplinary nature of this field, spanning robotics, control theory, human factors, and psychology, further complicates development, necessitating collaborative efforts to create systems that are both technically robust and user-friendly [15].

Guided by the motivation and gaps outlined above, this structured narrative (scoping-style) mini-review addresses three research questions: (RQ1) how haptic modalities and devices evolve across interaction stages; (RQ2) which control and stability/safety strategies are used and what trade-offs they impose; and (RQ3) how performance is evaluated and what remains missing for reproducible comparison. These questions define the problem structure for the review, are answered through the stage-by-stage synthesis in Sections 4–7, and are consolidated explicitly in Section 7.1 and in the Conclusion (Section 9).

In response to these questions, the paper makes four main contributions:

- **A five-category analytical lens** (Fig. 1) that links each interaction mode to the dominant haptic role, typical enabling devices/technologies, and the main open challenges.
- **A single unified comparative modelling lens** (Section 4.1) The equations are used only as representative abstractions, while the stage-specific interpretation is carried by Tables 6 and 7.
- **The primary synthesis output: a practical design-space matrix** (Table 7) that translates the across interaction modes synthesis into design-oriented cells covering dominant haptic purpose,

**Table 2**
Indicative evidence maturity, standards linkage, and prevalent interaction contexts across the interaction modes considered in this review.

| Interaction mode | Evidence maturity | Standards/formal guidance | Most prevalent interaction phases/application contexts |
|---|---|---|---|
| HRI | High | Indirect; emphasis is usually on stability, transparency, robustness, and application-specific protocols rather than dedicated haptic-contact limits. | Remote manipulation; contact-rich subtasks; surgical teleoperation; hazardous-environment control; training and simulation. |
| HRC | High and growing | Direct; collaborative operation is strongly shaped by ISO/TS 15066 force/pressure limits and related risk-assessment practice. | Shared workspace; incidental contact; hand-guidance and alignment; assembly assistance; ergonomic support. |
| pHRC | Moderate | Direct but incomplete; force limits remain relevant, but current guidance is less explicit for sustained physical coupling and ergonomic load sharing. | Continuous coupling; co-manipulation of bulky objects; rehabilitation-style assistance/resistance; sustained load exchange. |
| HRT | Emerging | Limited; there is no mature standards framework yet for AI-adaptive haptic cues, intent/confidence signalling, or authority negotiation. | Pre-contact coordination; intent/confidence communication; authority negotiation; shared autonomy; multi-agent teaming. |

*Note:* This table is intentionally qualitative. "Evidence maturity" summarises how established the reviewed literature is in each interaction mode, while "standards/formal guidance" indicates how directly existing safety or design guidance constrains haptic design decisions.

what the human mainly feels, main robot-side enablers, primary design priorities, and typical evaluation focus/main risks.
- **A qualitative evidence-grading summary** (Table 8) that classifies the main synthesis claims as strong, moderate, emerging, or speculative according to convergence in the literature, maturity of the subfield, and the extent of standards/benchmarking support.

The remainder of the paper is organised as follows: Section 2 summarises the review procedure; the subsequent sections review the five interaction modes in Fig. 1 with a consistent focus on (i) the haptic role, (ii) enabling technologies/devices, (iii) modelling/control choices, and (iv) distinctive unresolved challenges. Section 8 outlines future directions, and Section 9 summarises the study outcomes and open research needs.

## 2. Review methodology

This article was designed as a structured narrative, scoping-style mini-review rather than a full systematic review conducted under PRISMA-ScR [4]. The purpose was to identify a representative and analytically useful body of literature spanning the interaction modes considered in this review, from caged automation to human–robot teaming, rather than to exhaustively enumerate every publication in the field. To support transparency, the search was carried out across IEEE Xplore, Scopus, Web of Science, and Google Scholar for the period 2000–2025. The search syntax was adapted to each database, but followed the same logic by combining haptics-related terms (e.g., "haptic feedback", "force feedback", "tactile feedback", "kinesthetic feedback") with human–robot terms (e.g., "human–robot interaction", teleoperation, "human–robot collaboration", "physical human–robot collaboration", cobot*, "shared autonomy", and "human–robot teaming").

Records returned from different databases were pooled in a common reference list, after which duplicates were removed first by matching title/DOI/year and then by manual checking of near-duplicate entries and conference/journal versions of the same study. Screening was conducted in three steps: title screening, abstract/full-text screening for direct relevance, and backward/forward reference snowballing to capture influential papers closely connected to the retained core set. Because this is a structured narrative review rather than a systematic review, these steps were used to focus a representative and analytically useful set of sources, not to define a fully reproducible PRISMA-style selection pipeline. In practice, papers were retained when they spoke directly to haptic feedback, force/tactile interaction, or closely related control, stability, or safety issues in human–robot systems and helped inform at least one of the five interaction modes considered in the review. Papers were not retained when haptics was only peripheral, when the work focused on robotics without meaningful human interaction, when the contribution fell outside the review questions, or when an overlapping version was already represented in the retained set. For transparency, we reconstructed the screening-flow counts from the reference list and screening notes. The database searches initially produced approximately 187 records. After pooling the databases, 42 duplicate or overlapping records, including near-duplicate conference/journal versions, were removed, leaving 145 records for title screening. Title screening excluded 68 records. The remaining 77 records were assessed at abstract/full-text level, where 26 records were excluded because haptics was peripheral, the work did not involve meaningful human–robot interaction, the contribution fell outside the review questions, or an overlapping version was already represented in the retained set. Backward/forward snowballing then identified 17 additional candidate sources; 12 were retained and 5 were excluded after the same relevance checks. This produced the final set of 63 unique retained sources, and this exact number is used as the denominator for the source-accounting percentages reported below. For stage-wise accounting, these sources were coded according to the interaction mode(s) for which they directly supported the synthesis. Table 3 therefore reports both the approximate screening flow and the non-exclusive source–stage attributions. The five stage counts sum to 76 source–stage attributions because 13 retained sources were assigned to two interaction modes, while the remaining 50 sources were assigned to one mode only. Thus, 13/63 sources, or 20.6% of the retained set, are cross-stage sources. In this coding, no source was assigned to more than two interaction modes. For consistency of interpretation, the retained sources were then grouped by stage and application emphasis, and the same information was extracted across stages: haptic role, enabling devices/technologies, modelling/control strategy, evaluation approach, and unresolved challenges. Because this is a structured narrative review rather than a formal meta-analysis, the support for the main synthesis claims is graded qualitatively in Table 8 using four labels (strong, moderate, emerging, and speculative) based on convergence across studies, maturity of the subfield, consistency of reported outcomes, and the extent of standards/benchmarking support. Table 3 summarises the non-exclusive stage-wise distribution of the retained sources discussed in the synthesis.

For traceability, the cross-stage sources in this coding were the retained studies that supported more than one interaction mode, particularly sources spanning historical transition, teleoperation/haptics, shared-workspace collaboration, physical interaction control, and teaming: [1,6–9,11,14,17,20,25–28]. No uncited studies were used in the retained synthesis set.

## 3. Caged robots: Isolation and early automation

The emergence of industrial robotics in the mid-20th century represented a groundbreaking shift in automation, characterised by the deployment of robots within isolated environments, often termed 'caged robots', designed, see Fig. 2, to perform repetitive tasks with remarkable precision and efficiency [29]. Predominantly adopted in manufacturing industries such as automotive assembly, welding, painting,

**Table 3**
Approximate screening-flow and stage-wise source accounting for the retained synthesis set.

| A. Approximate screening-flow accounting | | | |
|---|---|---|---|
| Screening step | Considered | Excluded/removed | Remaining/retained |
| Database records identified and pooled | 187 | – | 187 |
| Duplicate/overlapping records removed | 187 | 42 | 145 |
| Title screening | 145 | 68 | 77 |
| Abstract/full-text relevance screening | 77 | 26 | 51 |
| Backward/forward snowballing candidates | 17 | 5 | 12 added |
| **Final unique retained sources** | – | – | 63 |

| B. Non-exclusive source–stage attributions within the final retained set | |
|---|---|
| Stage/source accounting | No. of sources/attributions |
| Caged robots | 13 |
| HRI | 30 |
| HRC | 10 |
| pHRC | 14 |
| HRT | 9 |
| **Total non-exclusive stage attributions** | **76** |
| **Unique retained sources** | **63** |
| **Cross-stage sources** | **13 (20.6%)** |

*Note:* The screening-flow values are approximate counts reconstructed from the reference list and screening notes, because this article is a structured narrative, scoping-style mini-review rather than a registered PRISMA-ScR review. The exact retained synthesis set contains 63 unique sources. Stage counts are non-exclusive because some retained sources inform more than one interaction mode. The five stage counts therefore sum to 76 source–stage attributions, not 76 unique sources. This total consists of 50 single-stage sources and 13 sources assigned to two stages, giving 63 unique retained sources in total. The cross-stage proportion is therefore $13/63 = 20.6\%$.

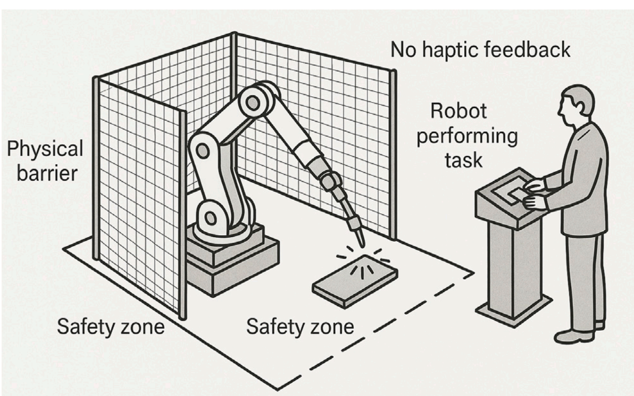


**Fig. 2.** Caged robot showing isolation and lack of haptic feedback in early automation.

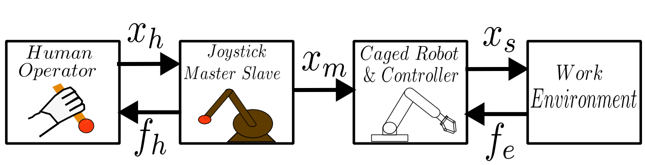


**Fig. 3.** Baseline non-haptic command teleoperation in a caged robot cell, with no closed-loop force feedback to the operator.

and material handling, these robotic systems operated behind physical barriers to ensure worker safety [18,19]. This isolation was a strategic design decision necessitated by the robots' high-speed operations and significant payload capacities, which posed substantial risks of injury from collisions or malfunctions [9,30]. By segregating robots from human workers, caged systems significantly boosted productivity and reduced workplace accidents; however, this came at the cost of flexibility, as real-time human intervention was impractical in situations requiring adaptive decision-making or rapid adjustments [25]. Tasks such as reprogramming, troubleshooting, or maintenance demanded system shutdowns and entry into secured zones, limiting the adaptability of these configurations in dynamic or intricate production settings [1].

In caged industrial deployments, closed-loop haptic feedback (i.e., force/tactile cues reflecting robot–environment interaction) was typically absent. Where early remote operation existed, it was commonly position/velocity command-only (e.g., jogging/teaching) rather than bilateral force-reflecting teleoperation; for this reason, haptic teleoperation is treated in the HRI stage (Section 4). Where remote operation existed, joysticks primarily served as unidirectional command devices (master interfaces), so the operator's interaction was largely limited to issuing motion commands rather than receiving force reflection from contact events. Accordingly, in Fig. 3 the operator applies an input force $f_h$ at position $x_h$ to generate commands for the slave robot (position $x_s$), while the environment contact force $f_e$ at the slave–environment interface is not fed back as real-time tactile or kinesthetic information. This baseline is intentionally contrasted with Fig. 4, where teleoperation becomes haptic-enabled and contact interaction can be rendered back to the operator through force-reflecting feedback. This clarification aligns our description of the caged-robot stage as having minimal/no haptic feedback compared with later bilateral teleoperation and physical collaboration [14,26,27].

Caged industrial robots emerged in the 1960s (e.g., the Unimate system) and matured through the 1980s as manufacturers improved speed, repeatability, and payload capacity for high-volume production [29]. Safety practice for these high-energy systems was formalised through standards such as ANSI/RIA R15.06 and ISO 10218-1, which effectively codified physical separation, safeguarded access, and emergency stop mechanisms as the dominant protection strategy [17]. Importantly, these safety protocols were not developed in a vacuum; rather, they were strengthened in response to real industrial harm. Early deployments saw severe accidents, including the fatal incident involving Robert Williams at Ford's Michigan facility (1979) and the death of Kenji Urada at Kawasaki Industries in Akashi (1981). The earliest version of the ANSI/RIA R15.06 safety standard was published later (1986), reflecting the historically reactive nature of safety formalisation in high-energy industrial automation. This historical lesson is relevant for the transition to AI-mediated Human–Robot Teaming (HRT): as autonomy and AI-adaptive haptic cues are introduced, safety requirements should be anticipated and validated proactively, rather than updated only after adverse events. In this context, robots were typically deployed for deterministic, pre-programmed tasks (often through early CNC-style programming paradigms), prioritising throughput and repeatability over real-time adaptation [1,25].

Importantly, haptic feedback did not “fail” to appear as a missed opportunity; rather, it was largely unnecessary and technically unattractive under the prevailing assumptions. Physical barriers removed the need for continuous human-in-the-loop contact regulation, and the dominant tasks rarely required real-time touch-based sensing or bidirectional force exchange. In addition, stable high-bandwidth force reflection and contact-aware compliance required sensing, actuation, and control maturity that was not standard in early industrial deployments, while safety and liability concerns discouraged any interface that could invite close-proximity operation [9,26]. The key lesson carried into the more interactive interaction modes is that, once separation is relaxed, “safety by fencing” must be complemented (or replaced) by “safety by design and control”, including force/torque sensing, compliant interaction control (e.g., impedance/admittance), and stability-oriented haptic architectures, which becomes increasingly important across HRI teleoperation, HRC/pHRC, and HRT [14,27,28].

## 4. Human–Robot Interaction (HRI): Teleoperation and haptic commands

Within the analytical lens used in this review, Human–Robot Interaction (HRI) denotes interaction modes in which humans and robots exchange commands and information with limited direct physical contact. It is not intended as a strictly chronological stage that must occur before HRC or HRT in every application; rather, it captures a dominant operating configuration in which haptic feedback is primarily used to enhance operator control and comprehension by engaging the sense of touch. This feedback, encompassing tactile and kinesthetic sensations, serves to signal system states, provide resistance in virtual interfaces, or replicate robotic dynamics, thereby improving the intuitiveness and efficacy of interactions [5,14,25].

Teleoperation, a cornerstone of HRI, facilitates remote robotic control, with haptic interfaces delivering force and tactile feedback, see Fig. 4, to create a sense of immersion in distant environments [5,27,31]. This functionality is critical in domains such as robotic surgery, space exploration, and hazardous material management, where direct human presence is infeasible or risky [30,32,33]. For example, in robotic-assisted surgery, systems like the da Vinci Surgical System enable surgeons to manipulate instruments remotely, with haptic feedback relaying tissue resistance and tool forces [5]. In space exploration, operators on Earth guide Mars rovers across uneven terrain, relying on haptic cues despite significant communication delays [31]. Achieving ‘transparency’, where operators perceive the remote environment accurately, is a key objective in teleoperation, though it is challenged by latencies, dynamic uncertainties, and environmental variability, which can compromise feedback fidelity and system stability [2,32,34,35]. Beyond teleoperation, HRI includes command-based interactions where haptic feedback conveys system states or provides virtual resistance, as seen in gesture-based or joystick-controlled interfaces that enhance natural communication [27,36]. In these setups, operators employ haptic devices, such as force-feedback joysticks [37], wearable sensors, or mechatronic controllers, to issue commands, receiving tactile or kinesthetic cues about the robot’s status or environment [5,6]. For instance, in industrial teleoperation, a haptic joystick might guide a robotic arm through assembly tasks, with resistance indicating obstacles or contact forces [35,38]. Similarly, virtual reality training platforms use haptic feedback to simulate robotic responses, such as the weight of a lifted object or the stiffness of a surface, enabling operators to hone skills in a controlled setting [7,36,39].

Evidence for the benefits of haptic feedback in HRI is primarily drawn from controlled user studies in teleoperation and interface-mediated training, where performance is quantified using objective metrics such as task completion time, success rate, path/pose error, collision counts, and contact-force overshoot, alongside subjective measures including workload (e.g., NASA-TLX) and perceived situational awareness. A commonly cited quantitative synthesis in this area is the older teleoperation-focused meta-analysis by Nitsch and Färber [16], which pooled 32 studies involving 712 participants and reported a large overall task-performance effect of haptic feedback (Hedges’ $g = 0.96$, 95% CI 0.71–1.21), but also substantial heterogeneity ($Q = 92.75$, $I^2 = 66.6\%$). Their moderator analysis further suggested larger but more heterogeneous effects in virtual setups ($g = 1.11$, $I^2 = 74.1\%$) than in real teleoperation setups ($g = 0.74$, $I^2 = 35.1\%$), reinforcing that the magnitude of benefit is task- and setup-dependent rather than uniform across HRI. For clarity, this meta-analysis is used here only to support a task-performance claim in teleoperation, not as direct evidence for a broad general claim about environment awareness. The latter is treated more narrowly as task-specific contact or state awareness, supported by teleoperation and haptics studies in which force/tactile cues help operators perceive contact forces, virtual constraints, or robot/environment status [5,7,14,27]. Overall, haptic feedback can improve task performance and contact regulation in some teleoperation settings, but the benefit remains task-, interface-, and setup-dependent [2,16]. Beyond objective performance, haptic feedback can increase user engagement and perceived controllability, but it also introduces design challenges, including cue calibration (to avoid sensory overload) and tight temporal synchronisation with robot motion to preserve responsiveness and trust [6,7].

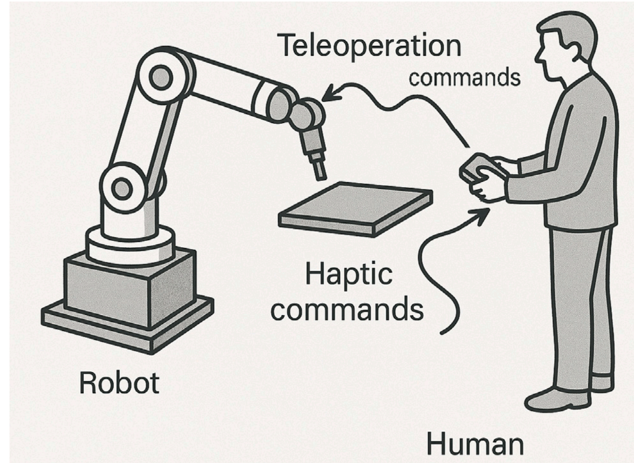


**Fig. 4.** Teleoperation with haptic feedback for enhanced robot control in HRI.

The role and design of haptic feedback are partly application-dependent. In *surgical teleoperation*, Table 4, haptics is primarily used to support fine contact interaction (e.g., perceiving tissue/tool forces, maintaining delicate contact, and improving precision), where safety is dominated by avoiding unintended tissue damage and excessive tool forces; consequently, force scaling, virtual fixtures, and conservative limits are common, and performance is often reported in terms of accuracy, error rates, force overshoot, and tissue-safe interaction metrics [5,14,40]. In *industrial shared-workspace collaboration*, haptics more often supports guidance, contact detection, and ergonomic load-sharing during co-manipulation, where safety is shaped by human injury risk under close proximity and is commonly framed through force/pressure limits and standards compliance (e.g., ISO/TS 15066) alongside throughput and quality measures [9,11,17]. Despite these differences, several aspects are largely universal across domains: stable and predictable interaction (especially under uncertainty/delay), intuitive cue mappings that avoid sensory overload, and evaluation that jointly reports task performance and human factors (e.g., workload and trust) rather than performance alone [2,15,16].

Command-based haptics in HRI can be understood most clearly by separating what is intentionally delivered to the human through different sensory channels. Kinesthetic feedback renders net forces,

**Table 4**
Illustrative comparison of haptic design priorities across surgical teleoperation and industrial collaboration.

| Design aspect | Surgical teleoperation | Industrial collaboration |
|---|---|---|
| Dominant haptic purpose | Fine contact perception and high-precision manipulation during tool–tissue interaction. | Guidance, contact mediation, ergonomic co-manipulation, and shared-workspace assistance. |
| Typical interfaces/devices | Master console or grounded kinesthetic device, often combined with virtual fixtures and force scaling. | Cobot hand-guiding, wrist force/torque sensing, joint-torque sensing, and impedance/admittance control with safety limits. |
| Primary safety concern | Avoiding tissue damage and excessive tool forces; conservative interaction limits dominate. | Limiting human injury risk during close-proximity operation; ISO/TS 15066 force/pressure limits and risk assessment dominate. |
| Common evaluation focus | Accuracy, error, force overshoot, contact quality, and tissue-safe interaction metrics. | Task time and quality, peak/impulse/contact forces, workload, comfort, and trust. |
| What remains largely consistent | Need for stable and predictable interaction, intuitive cue mapping, overload management, and joint reporting of task performance with human-factor outcomes. | |

*Note:* This table is illustrative rather than exhaustive. Its purpose is to show how the same haptic design problem is framed differently across two widely studied HRI contexts.

resistance, guidance, or boundary constraints through grounded devices; tactile/cutaneous feedback stimulates the skin more locally; and vibrotactile cues are often used to communicate events, thresholds, warnings, or directional prompts with lower mechanical load [5–7]. In this interaction mode, what the operator feels is typically a deliberately designed interface output derived from robot-side measurements or estimates (e.g., contact force, position error, virtual fixtures, or state/confidence information), rather than from direct body-to-body force exchange with the robot itself. Multimodal feedback, combining haptic, visual, and auditory signals, can further improve comprehension and performance, but requires careful synchronisation to avoid sensory conflicts or overload [16,27,41].

In essence, command-based haptics in HRI enables a seamless and efficient command exchange by leveraging touch, enhancing operator understanding of robotic states and improving control. As robotics progresses, advancing haptic feedback mechanisms will be instrumental in achieving deeper human–robot collaboration and teaming [9,19,27]. Research continues to explore novel haptic interfaces and control strategies to address current limitations, promising even greater integration in future applications [35,42].

### 4.1. Unified comparative modelling lens

The modelling material is presented once in a unified subsection rather than being repeated in separate HRI, HRC, pHRC, and HRT subsections. The purpose is not to derive design-ready controllers, but to provide a compact notation-level progression showing how the same interaction primitives are re-used across interaction modes. All symbols and units used in Eqs. (1)–(11), including $F_h$, $F_r$, $K_v$, $M_r$, $B_r$, $K_r$, $F_{\max}$, $\gamma$, $\alpha$, and $\beta$, are defined in Table 5. Eqs. (1)–(11) should therefore be read as representative abstractions for comparison only. The stage-specific interpretation is embedded in Tables 6 and 7.

**HRI: virtual coupling and impedance.** In interface-mediated HRI and teleoperation, the haptic channel is commonly described using virtual coupling or impedance-type abstractions. A simple virtual spring maps position error into rendered haptic force:

$$F_h = -K_v\left(x_s - x_d\right). \tag{1}$$

Shown in Fig. 5, a compact impedance abstraction then adds inertia and damping, capturing the basic mass–spring–damper "feel" of the rendered interaction:

$$M_r\ddot{x}_s + B_r\dot{x}_s + K_r x_s = F_h + F_r. \tag{2}$$

**HRC: local compliance and force limiting.** In shared-workspace HRC, the same primitives are interpreted mainly as local compliance and safety constraints rather than as remote-transparency tools. A representative desired impedance around a task reference can be written as:

$$M_d\ddot{e} + B_d\dot{e} + K_d e = -F_h, \tag{3}$$

with the simplified robot dynamics represented as:

$$M_r\ddot{x} + B_r\dot{x} = F_r - F_h. \tag{4}$$

A corresponding computed force can be expressed compactly as:

$$F_r^{\text{computed}} = M_r\left(\ddot{x}_d + M_d^{-1}(-F_h - B_d\dot{e} - K_d e)\right) + B_r\dot{x} + F_h. \tag{5}$$

The key HRC point is the safety-bounded interpretation, which can be represented by:

$$F_r = \operatorname{sat}\left(F_r^{\text{computed}}, F_{\max}\right). \tag{6}$$

**pHRC: admittance-style responsiveness.** In pHRC, sustained physical coupling makes the human-applied force a primary input that should shape motion. A representative 1-DOF admittance-style velocity law is:

$$\dot{x}_d = \dot{x}_0 + \frac{1}{B_d}\left(F_h - K_d(x - x_d)\right). \tag{7}$$

Force limiting remains necessary during sustained coupling and can again be expressed as:

$$F_r = \operatorname{sat}\left(F_r^{\text{computed}}, F_{\max}\right). \tag{8}$$

**HRT: intent inference, blending, and adaptive assistance.** In HRT, the modelling emphasis shifts from contact regulation alone to intent-aware coordination. A compact Bayesian intent update can be written as:

$$P\left(g_i \mid o_{1:t}\right) = \frac{P\left(o_t \mid g_i\right) P\left(g_i \mid o_{1:t-1}\right)}{P\left(o_t \mid o_{1:t-1}\right)}. \tag{9}$$

The inferred intent or confidence can then be used in a shared-autonomy blending law:

$$u = (1-\gamma)u_h + \gamma u_r. \tag{10}$$

Finally, a simple force-sharing abstraction can represent adaptive physical assistance:

$$F_r = \alpha F_h + \beta \dot{F}_h. \tag{11}$$

These expressions deliberately remain compact. They are not proposed as complete controllers and do not capture multi-contact coupling, nonlinear friction, actuator saturation, detailed human neuromechanics, or full communication-channel dynamics. Their role is to support the cross-stage comparison in Tables 6 and 7 (see Fig. 5).

## 5. Human–Robot Collaboration (HRC): Shared workspace with force feedback

The boundary between HRC and pHRC is treated here as a conceptual gradient rather than a binary switch. We use HRC to denote shared-workspace collaboration in which contact is mainly intermittent, incidental, or task-guiding, whereas pHRC denotes cases where

**Table 5**
Notation and units used in the mathematical models across HRI, HRC, pHRC, and HRT.

| Symbol | Meaning | Unit |
|---|---|---|
| *Common mechanical variables* | | |
| $x$, $x_s$, $x_d$ | Actual position, robot/slave position, and desired/reference position in the 1-DOF translational abstraction. | m |
| $\dot{x}$, $\dot{x}_s$, $\dot{x}_d$, $\dot{x}_0$ | Velocity, slave velocity, desired/reference velocity, and nominal velocity. | $\mathrm{m\,s^{-1}}$ |
| $\ddot{x}$, $\ddot{x}_s$, $\ddot{x}_d$ | Acceleration, slave acceleration, and desired/reference acceleration. | $\mathrm{m\,s^{-2}}$ |
| $e$, $\dot{e}$, $\ddot{e}$ | Position, velocity, and acceleration error, with $e = x - x_d$. | m; $\mathrm{m\,s^{-1}}$; $\mathrm{m\,s^{-2}}$ |
| $F_h$, $F_r$, $F_e$, $F_{\max}$, $F_r^{\text{computed}}$ | Human-applied force, robot force, environment/contact force, allowable force limit, and computed unsaturated robot force. | N |
| $\mathrm{sat}(\cdot, F_{\max})$ | Saturation operator used to bound the commanded or computed robot force by the allowable force limit $F_{\max}$. | Operator; output in N |
| *Impedance/admittance parameters* | | |
| $K_v$, $K_r$, $K_d$ | Virtual or desired stiffness parameters. | $\mathrm{N\,m^{-1}}$ |
| $B_r$, $B_d$ | Virtual or desired damping parameters. | $\mathrm{N\,s\,m^{-1}}$ |
| $M_r$, $M_d$ | Virtual or desired inertia (mass) parameters. | kg |
| *HRT/shared-autonomy variables* | | |
| $u$, $u_h$, $u_r$ | Blended, human, and robot control commands in the shared-autonomy law. | Application-dependent; must be consistent within the chosen control channel (e.g., N, $\mathrm{m\,s^{-1}}$, or $\mathrm{rad\,s^{-1}}$) |
| $\gamma$ | Shared-autonomy blending/confidence weight. | Dimensionless |
| $g_i$ | Candidate human goal/intention hypothesis. | Dimensionless index |
| $o_t$, $o_{1:t}$ | Observation at time $t$ and observation history used in Bayesian intent inference. | Application-dependent observation units |
| $P(\cdot)$ | Probability/belief terms in the Bayesian update. | Dimensionless |
| $\alpha$ | Proportional force-sharing gain in $F_r = \alpha F_h + \beta \dot{F}_h$. | Dimensionless |
| $\beta$ | Derivative force-sharing gain multiplying $\dot{F}_h$. | s |

*Note:* Unless otherwise stated, the 1-DOF mechanical models are written in translational SI units. For rotational implementations, the directly analogous quantities are angle (rad), angular velocity ($\mathrm{rad\,s^{-1}}$), angular acceleration ($\mathrm{rad\,s^{-2}}$), torque (N m), rotational stiffness ($\mathrm{N\,m\,rad^{-1}}$), rotational damping ($\mathrm{N\,m\,s\,rad^{-1}}$), and rotational inertia ($\mathrm{kg\,m^2}$).

**Table 6**
Unified interpretation of the compact modelling progression across interaction modes.

| Stage | Representative abstraction | Key parameters | Interpretive role in this review |
|---|---|---|---|
| HRI | Virtual coupling/impedance, Eqs. (1)–(2) | $K_v$; $M_r, B_r, K_r$ | Used to discuss transparency, rendered contact feel, and stability/robustness under delay or uncertainty. Higher stiffness can improve crispness but may increase oscillation risk; damping improves robustness but can reduce responsiveness. |
| HRC | Desired impedance and force saturation, Eqs. (3)–(6) | $M_d, B_d, K_d$; $F_{\max}$ | Used as a compact way to express safe co-location, compliant response, contact detection, and standards-driven force limiting. The equations are not presented as an HRC controller derivation, but as a notation for the design shift from remote transparency to bounded shared-workspace contact. |
| pHRC | Admittance-style response and safety saturation, Eqs. (7)–(8) | $B_d, K_d$; $F_{\max}$ | Used to represent sustained physical coupling, where measured human-applied forces directly shape robot motion. Lower damping increases responsiveness, while stiffness and saturation support task guidance, comfort, and safety. |
| HRT | Intent inference, shared-autonomy blending, and adaptive force sharing, Eqs. (9)–(11) | $\gamma$; $\alpha, \beta$; confidence/adaptation variables | Used to describe how haptics can communicate intent, confidence, authority, and assistance level. The main risk is no longer only contact instability, but also inconsistent feel, mode confusion, over-assistance, and lack of verifiable safety for adaptive cues. |

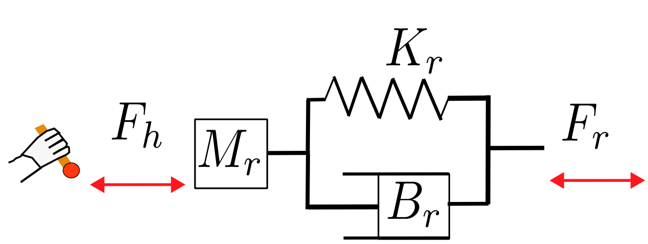


**Fig. 5.** Block diagram of a 1-Dof Haptics interface.

sustained physical coupling and continuous bidirectional force negotiation are central to the task. This distinction is useful for organising the review, but it is partly an analytical choice: specific systems may sit near the boundary, move between HRC and pHRC during different task phases, or be classified differently depending on whether the analyst emphasises workspace sharing, contact duration, force exchange, or load sharing.

Within the analytical lens used in this review, Human–Robot Collaboration (HRC), often implemented using cobots, denotes shared-workspace interaction modes in which humans and robots perform tasks alongside one another, with force feedback used to facilitate safe and efficient interaction. It should not be read as a universally later step than HRI; in practice, HRC can coexist with other interaction modes depending on task design, proximity, and the nature of contact. In HRC, the shared workspace allows for simultaneous task execution, with force feedback playing a crucial role in ensuring safe and efficient collaboration.

In HRC, see Fig. 6, robots are designed to operate alongside humans, often in industrial settings such as assembly lines, where they share

**Table 7**
Primary synthesis output: design-space matrix translating the across interaction modes synthesis into practical design and evaluation considerations.

| Interaction mode | Dominant haptic purpose | What the human mainly feels | Main robot-side enablers | Primary design priorities | Typical evaluation focus/main risk |
|---|---|---|---|---|---|
| Caged automation | Baseline reference; little or no human-facing haptics | Minimal interface feel; no closed-loop contact reflection | Physical separation, safeguarded motion, deterministic task programming | Productivity and safety by separation | Throughput/repeatability; main risk is loss of flexibility rather than haptic instability |
| HRI | Remote rendering and command guidance | Force reflection, kinesthetic resistance, tactile/vibrotactile alerts | Master device, environment sensing/estimation, virtual coupling/impedance, delay-robust control | Transparency vs. stability; cue legibility under uncertainty | Task success, transparency, workload, stability under delay; main risk is oscillation or misleading feel |
| HRC | Shared-workspace contact mediation | Hand-guidance resistance, virtual boundaries, incidental contact feel, warning cues | Force/torque or joint-torque sensing, impedance with saturation, collision/contact detection | Safe co-location, force limiting, intuitive guidance, standards compliance | Completion time, error, peak/contact forces, comfort; main risk is over-stiff or ambiguous contact response |
| pHRC | Sustained force negotiation and load sharing | Direct shared-load feel, assistance/resistance during co-manipulation, optional localised cutaneous augmentation | Admittance/impedance control, force sensing, direction-dependent gains, ergonomic tuning | Responsiveness vs. comfort, stable sustained contact, ergonomic assistance | Effort, force variability, comfort, task quality; main risk is fatigue, instability, or non-intuitive load sharing |
| HRT | Intent, confidence, and authority communication | Adaptive kinesthetic cues, shared-control feel, wearable cutaneous/vibrotactile prompts | Intent inference, blending/adaptive gains, confidence estimation, shared-autonomy logic | Legibility, non-coercive assistance, consistent feel across mode changes, verifiable adaptive safety | Fluency, trust, mode awareness, override success; main risk is mode confusion or over-assistance |

tasks like part handling or assembly operations. Force feedback is typically provided through haptic interfaces or direct physical interaction, enabling the robot to sense and respond to human-applied forces. This interaction is further clarified by the free body diagram in Fig. 7, which illustrates the forces involved: the human operator receives a force $F_h$ at position $x_h$, influencing the shared workspace at position $x_s$, while the robot responds with a force $F_r$, enabling a bidirectional force exchange that ensures safe and intuitive collaboration. Representative HRC applications include shared-workspace assembly and hand-guidance, where force cues support alignment and incidental contact regulation. When the same or a similar system enters a task phase with sustained physical coupling and continuous load sharing, we discuss that behaviour under pHRC (Section 6); the classification therefore follows the dominant interaction mode rather than the robot platform alone [18,19]. For example, in collaborative assembly, a human operator might guide a robot arm to position a component, with the robot providing force feedback to indicate resistance or alignment [18].

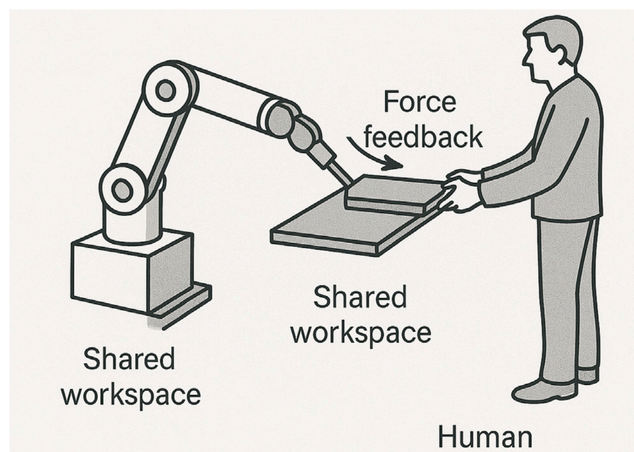


**Fig. 6.** Shared workspace in HRC with force feedback for safe collaboration.

To avoid repeating the generic motivations already discussed in Sections 4 and 6, we emphasise here the HRC-specific distinction between *felt interaction* and *designed feedback* in co-located shared-workspace operation. What the person feels in HRC may come from (i) intentionally shaped cues, such as resistance during hand-guidance, virtual boundaries, or vibrotactile warnings, and/or (ii) physical forces arising from incidental or task-related contact in the shared workspace. The latter can still inform the user, but it does not automatically constitute meaningful feedback unless it is made interpretable through compliant behaviour, force limiting, or explicit cue design. Accordingly, robot-side force/torque sensing, joint-torque estimation, contact detection, and impedance/admittance control are central not only for safety but also for determining whether a contact is merely tolerated, passively felt, or intentionally rendered as informative interaction [6,8,9,17,28]. Empirical evaluations in HRC are therefore typically reported using task-level outcomes (completion time and error), interaction-force measures (e.g., peak/impulse/contact frequency), and user-centred metrics (workload, comfort, and trust), rather than the transparency-focused emphasis that dominates remote HRI.

However, HRC with shared workspace and force feedback also presents challenges. Ensuring safety remains a primary concern, requiring robust sensing and control systems to detect human presence and adjust robot behaviour accordingly. The ISO/TS 15066:2016 standard provides guidelines for collaborative robot safety, emphasising the importance of force and pressure limits to prevent harm [17]. In practical haptic design, these limits should be translated into explicit controller requirements: the allowable force bound $F_{\max}$, rendered stiffness/damping, and any velocity or acceleration limits should be chosen so that expected and worst-case contact forces remain below the relevant body-region thresholds. They also affect interface design because contact area, end-effector shape, padding, and tool geometry determine whether a given interaction force becomes an acceptable or excessive pressure. Consequently, haptic guidance, virtual fixtures, warning cues, and power-and-force-limiting behaviour should be triggered before the estimated force/pressure approaches the ISO/TS 15066 limit, rather than only after the limit has been reached. Additionally, designing effective force feedback systems requires addressing issues like latency, accuracy, and the integration of multimodal feedback (e.g., visual and auditory cues) to avoid sensory overload [16]. In summary, HRC represents the transition to *co-located* collaboration in shared workspaces, where force feedback is most valuable for mediating intermittent contact, enabling hand-guidance/co-manipulation, and supporting intent/constraint communication under close-proximity safety limits, thereby bridging command-based HRI and the continuous force exchange characteristic of pHRC. As robotics technology

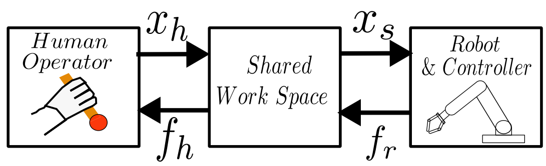


**Fig. 7.** Free body diagram illustrating the forces and interactions in a shared workspace during Human–Robot Collaboration (HRC).

advances, the development of more sophisticated force feedback mechanisms will be crucial for achieving higher levels of collaboration and teaming.

The HRC modelling expressions and their interpretation have been consolidated into the unified comparative modelling lens in Section 4.1, especially Table 6. This section therefore focuses on the HRC-specific interaction role, sensing/control enablers, evaluation measures, and practical safety implications.

## 6. Physical Human–Robot Collaboration (pHRC): Haptic force exchange

Within the analytical lens used in this review, Physical Human–Robot Collaboration (pHRC), as illustrated in Fig. 8, denotes interaction modes characterised by direct physical interaction and sustained force exchange during joint task execution. As noted in Section 5, the HRC/pHRC boundary is not a binary switch but a conceptual gradient. We separate pHRC from HRC for analytical clarity, while recognising that some systems may be classified differently depending on the task phase, contact duration, and whether the main emphasis is contact mediation or sustained force/load sharing. In pHRC, the exchange of forces between the human and the robot is central, necessitating sophisticated control strategies to ensure safe, efficient, and intuitive collaboration. This interaction is visually represented in Fig. 9, which depicts a free body diagram where the human operator applies a force $f_h$ at position $x_h$, influencing the shared workspace at position $x$, while the robot and controller respond with position, enabling bidirectional force exchange. In pHRC, the most distinctive applications are those that require *continuous* physical coupling and bidirectional force negotiation; for example co-manipulation of bulky or awkward objects, closely coupled hand-over/hand-guidance, and tightly coupled rehabilitation exercises where the robot shapes assistance/resistance while maintaining user comfort and safety [11,20].

**HRC versus pHRC (why pHRC is distinct).** The distinction between HRC and pHRC is used here as an analytical distinction along a continuum of physical coupling, not as a fixed classification rule imposed by the literature. Compared with HRC, where force feedback mainly mediates *intermittent* contacts and constraint communication in a shared workspace, pHRC is defined here by *continuous physical coupling* and sustained bidirectional force exchange. Thus, the same platform could reasonably be discussed as HRC during intermittent hand-guidance or contact-mediation phases, and as pHRC during sustained co-manipulation or load-sharing phases. While both HRC and pHRC are co-located, their dominant interaction mode differs: HRC typically involves shared-workspace collaboration with *intermittent* contact and guidance (force feedback supports contact detection, compliant response, and standards-driven force limiting), whereas pHRC involves *sustained* physical coupling where forces are continuously exchanged to negotiate load sharing and motion. This difference motivates the modelling/control shift discussed in the synthesis tables: HRC is described mainly through impedance-type compliance and explicit force saturation for safe shared-workspace contact, whereas pHRC is more naturally associated with admittance-style responsiveness that maps measured external forces into motion for intuitive co-manipulation. Here, haptic interaction is not merely an auxiliary cue; it becomes the primary channel through which the human and robot negotiate load sharing, compliance, and task progression in real time (e.g., co-manipulation, hand-over/hand-guidance, and physical assistance) [9,11].

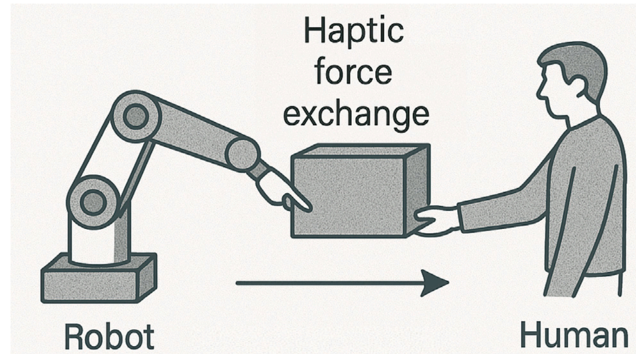


**Fig. 8.** Haptic force exchange in pHRC during intuitive physical cooperation.

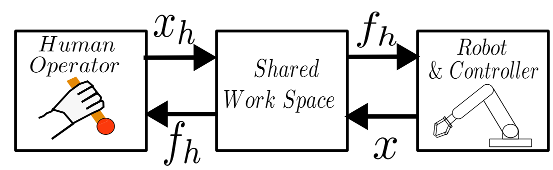


**Fig. 9.** Free body diagram illustrating the forces and interactions in a shared workspace during Physical Human–Robot Collaboration (pHRC).

pHRC is most commonly enabled by collaborative manipulators with torque/force control and integrated sensing (e.g., wrist force/torque sensors, joint-torque sensing, and contact/tactile sensing) combined with compliant actuation strategies (impedance/admittance) that shape safe, intuitive physical behaviour [8,28,29]. In this interaction mode, what the person actually feels is inseparable from the mechanics of coupling: weight sharing, inertia, compliance, guidance, resistance, and transient mismatches are perceived directly through the body during co-manipulation or physical assistance. Part of this sensation is the raw consequence of physical interaction, while part of it is intentionally shaped by the controller or supplemented through dedicated interfaces. For that reason, robot-side sensing and compliance control are not merely back-end implementation details; they determine how external forces are interpreted and re-expressed as motion, resistance, or stabilising behaviour, and wearable/skin-stimulation devices can add localised cutaneous or vibrotactile cues when direct contact alone is insufficient or undesirable [6,7,9,11].

The central open issues in pHRC arise from sustained energy exchange and variability of human neuromechanics: (i) maintaining stable behaviour under rapidly changing human impedance and multi-contact interactions (avoiding oscillations or unintended force amplification) while preserving responsiveness [15,43]; (ii) guaranteeing safety beyond simple force limits, including pressure distribution, transient impacts, and collision detection during continuous contact [17,21]; (iii) distinguishing intentional guidance from disturbances/fatigue and adapting compliance without causing confusion or loss of trust; and (iv) the lack of standardised benchmarks that jointly report task performance, interaction forces, and human factors for reproducible comparison across pHRC systems [9] (see Fig. 8).

In summary, pHRC is best understood here as a distinct but partially overlapping interaction mode centred on sustained physical coupling. By enabling direct physical interaction, pHRC leverages the complementary strengths of humans and robots to achieve tasks that would be difficult or impossible for either to perform alone. As technology advances, the development of safer, more intuitive, and more efficient pHRC systems will continue to be a key focus in robotics research and application.

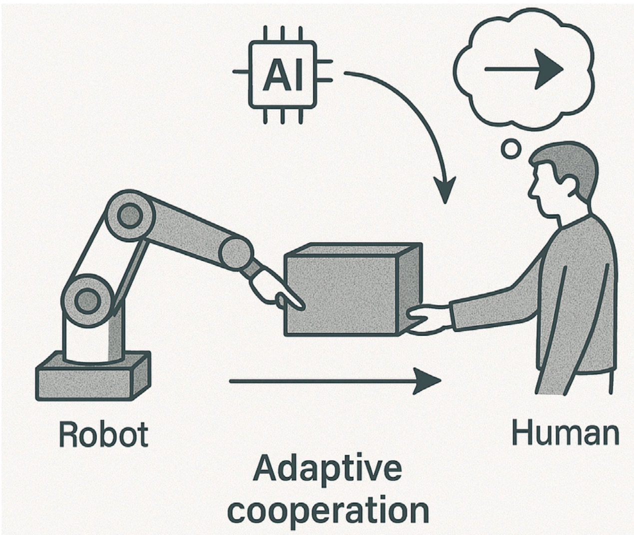


**Fig. 10.** Illustration of AI-driven haptic feedback in Human–Robot Teaming (HRT) for adaptive cooperation.

The pHRC admittance-style expression and force-saturation abstraction are now presented in the unified comparative modelling lens in Section 4.1. The stage-specific interpretation is summarised in Table 6, while Table 7 gives the practical design and evaluation implications for sustained physical coupling, load sharing, comfort, and safety (see Fig. 10).

## 7. Human–Robot Teaming (HRT): AI-driven haptics for adaptive cooperation

In this review, Human–Robot Teaming (HRT, illustrated in Fig. 10, is treated less as a strictly later stage and more as a coordination layer in which haptic feedback moves beyond contact regulation to become an *implicit communication channel* for coordination. In practical terms, HRT may be instantiated on top of HRI, HRC, or pHRC, depending on how intent communication, authority negotiation, and shared autonomy are implemented. Haptic cues are therefore used to convey the robot's intent, task constraints, and confidence in real time so that the human can anticipate, negotiate, or override the robot's assistance during joint action. AI is treated here as an enabling layer that *modulates* these haptic cues (content, timing, and intensity) based on inferred intent and uncertainty, rather than as the primary focus of the section [12,13,44].

**Typical haptic technologies/devices in HRT.** HRT systems commonly employ (i) *kinesthetic* guidance through force-feedback handles/joysticks or instrumented collaborative interfaces that can render directional guidance, resistance, or boundary cues; and (ii) *cutaneous/wearable* devices (e.g., vibrotactile bands or fingertip/palm stimulation) when it is preferable to communicate intent without strong physical coupling [6,7,13]. These interfaces are especially useful for communicating shared-control authority (e.g., "robot is confident" vs. "human has priority") and for delivering proactive guidance without demanding continuous visual attention.

Fig. 11 summarises this haptic teaming loop: the human's physical input influences the shared workspace while an AI controller adapts the robot response and the haptic cues in a context-dependent manner.

In contrast to pHRC, where haptics primarily supports load sharing and continuous force negotiation, HRT uses haptics to support *coordination and decision-making* during joint action. Typical haptic functions include: (i) *intent communication* (rendering the robot's predicted goal or motion plan as a directional cue), (ii) *authority negotiation* (physical

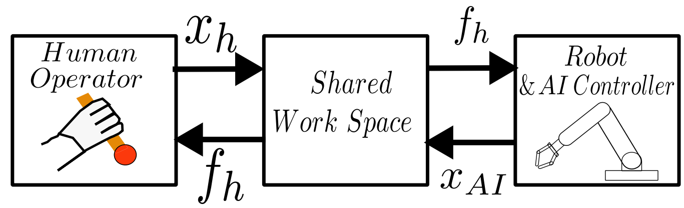


**Fig. 11.** Free body diagram of the simplified HRT interaction loop with human input, AI-guided robot response, and adaptive bidirectional force exchange.

signalling of shared-control weighting or "who leads"), and (iii) *proactive guidance* (subtle corrective cues that reduce conflicts and improve fluency in teaming) [13,45].

The open problems in HRT are not only AI-related, but specifically *haptics-in-the-loop*: (i) designing cues that are legible and informative without becoming coercive or causing over-reliance; (ii) maintaining stability and predictable feel when gains are scheduled online by an AI module (risking oscillations or inconsistent interaction); (iii) avoiding mode confusion and sensory overload when haptic, visual, and autonomy cues change concurrently; and (iv) the lack of standardised evaluation protocols that jointly report teaming fluency (conflict/overrides), task performance, and human factors (workload, trust, comfort) for AI-adaptive haptic teaming [7,22].

The HRT intent-inference, shared-autonomy blending, and adaptive force-sharing expressions are consolidated in the unified comparative modelling lens in Section 4.1. Their role in this review is interpretive rather than prescriptive: they show how haptics can communicate intent, confidence, and authority in teaming, while Tables 6 and 7 summarise the associated design priorities and risks.

### *7.1. Synthesis in relation to the research questions*

The review can be summarised directly in relation to the three research questions introduced in the abstract and the Introduction. First (RQ1), the evidence shows a clear shift in both the *form* and the *purpose* of haptic feedback across the analytical interaction modes used in this review (Fig. 1, Table 1): it is largely absent in caged automation, becomes primarily a channel for force/tactile rendering and command cues in HRI teleoperation, shifts towards contact mediation and hand-guidance in shared-workspace HRC (often enabled by cobots and force/torque sensing), and then becomes central in pHRC where sustained physical coupling requires continuous force negotiation and ergonomic load sharing. In HRT, haptics extends beyond contact regulation to communicate intent and confidence and to support authority negotiation through adaptive kinesthetic and/or wearable cutaneous cues.

Second (RQ2), the dominant modelling and control perspective changes as interaction tightens, as now summarised in the unified comparative modelling lens (Section 4.1) and in Tables 6 and 7. HRI is most often framed through virtual coupling/impedance to manage transparency and robustness under uncertainty (and, in teleoperation, delay). In HRC, similar primitives are re-purposed as a local interaction policy, typically combining desired impedance with explicit saturation to satisfy standards-driven safety limits. pHRC commonly favours admittance-style response, since mapping measured human-applied forces into motion is a natural way to achieve responsive co-manipulation without a network-mediated channel. HRT then builds on these foundations by introducing intent-aware blending and adaptive gains; this improves flexibility and fluency but raises new practical issues around consistent "feel", mode confusion, and verifiable stability when parameters vary online. The new design-space matrix makes these shifts explicit in practical terms by pairing each interaction mode with its dominant haptic purpose, enabling mechanisms, design priorities, and main evaluation focus.

**Table 8**
Qualitative evidence-grading summary for the main synthesis claims in this review.

| Major claim | Representative basis in the reviewed literature | Support | Why this grade |
|---|---|---|---|
| Haptic feedback becomes progressively more functionally important as interaction shifts from caged automation towards close-proximity collaboration and teaming. | Across interaction modes surveys and historical syntheses across caged automation, HRI, HRC, and teaming [1,9,14]. | Strong | Consistent with the broad literature surveyed here and repeatedly reflected across multiple mature subfields, even though the interaction modes are used analytically rather than as a strict historical ladder. |
| In HRI teleoperation, force/kinesthetic rendering can improve task performance in some teleoperation settings and support task-specific contact or state awareness, but the benefit is not uniform and transparency must be balanced against stability and delay robustness. | Teleoperation meta-analysis and task-specific haptics/stability literature [2,14–16,27]. | Moderate | Nitsch and Färber work [16] provide quantitative support for task-performance benefits, but the reported effect was heterogeneous; contact/environment awareness is supported more indirectly through task-specific teleoperation and haptics studies rather than by that meta-analysis alone. |
| In HRC, force/torque sensing and compliant control improve safe shared-workspace interaction, hand-guidance, and contact regulation. | Industrial HRC surveys and collaborative-robot safety guidance [9,17,28]. | Strong | Supported by a mature literature and reinforced by direct standards linkage, although implementation details remain application-specific. |
| In pHRC, sustained physical coupling shifts design emphasis towards admittance/impedance tuning, ergonomic load sharing, and comfort. | pHRC/co-manipulation literature and admittance-control reviews [11,20,21]. | Moderate | Recurrent support exists, but the evidence is more heterogeneous and less standardised than in HRI/HRC, with stronger dependence on task, user variability, and controller tuning. |
| In HRT, haptics can communicate intent, confidence, and shared-control authority in adaptive coordination. | Shared autonomy, haptic guidance, and explainable teaming literature [12,13,22]. | Emerging | Promising and well motivated, but currently supported by a smaller and less standardised evidence base than earlier interaction modes. |
| AI-adaptive haptic cues will generalise robustly across tasks while remaining legible, trustworthy, and verifiably safe. | Early teaming and explainable/shared-autonomy literature, together with broader concerns from AI governance in robotics [12,22,46]. | Speculative | Conceptually plausible and attractive, but not yet supported by sufficiently mature benchmarking, validation protocols, or stage-specific safety guidance. |

*Note:* These labels are qualitative summary judgments for this structured narrative review, not a formal GRADE-style appraisal. **Strong** = repeated support across a mature literature with good convergence; **Moderate** = recurring support but more heterogeneous, task-dependent, or only partly supported by direct quantitative evidence; **Emerging** = promising but currently limited or less standardised evidence; **Speculative** = conceptually plausible but not yet well validated.

Third (RQ3), evaluation practice is broadly consistent in the *types* of measures reported but less consistent in how they are combined and benchmarked. Across stages, studies typically quantify task outcomes (time, error, success), interaction forces (peak, impulse, contact frequency/variability), and human factors (workload, comfort, trust), yet the balance and reporting detail differ markedly by application and stage (Tables 2–7). The most persistent cross-stage limitation is the lack of reproducible benchmarks that jointly report these dimensions under comparable task definitions, together with limited stage-specific safety and evaluation guidance for AI-adaptive haptic cues in HRT. Table 8 summarises the main synthesis claims and grades their present support qualitatively as strong, moderate, emerging, or speculative.

## 8. Future directions

The analytical lens developed in this review, spanning caged automation, HRI, HRC, pHRC, and HRT, highlights how haptic design priorities change across different interaction modes of proximity, contact, and authority sharing. Haptic systems have been instrumental across these interaction modes, providing intuitive sensory channels that enhance safety, efficiency, and cooperative performance. Looking ahead, several avenues promise to shape the next generation of haptic-enabled robotic systems. This section outlines three key directions: advances in AI-driven haptic interfaces, the role of multi-modal haptic feedback in teamwork, and the critical ethical and safety considerations in HRT applications; Fig. 12. These areas build on the technological foundations discussed earlier and address the challenges and opportunities as robots become true teammates.

### *8.1. Advances in AI-driven haptic interfaces*

The integration of artificial intelligence (AI) with haptic interfaces is poised to significantly advance human–robot interaction, particularly within the context of human–robot teaming (HRT). Traditional haptic systems, often reliant on static models and predefined responses, face limitations in adapting to the dynamic and nuanced nature of human behaviour [23,47]. AI presents a transformative approach by enabling haptic interfaces to become adaptive, context-aware, and personalised, thereby enhancing collaborative performance in complex tasks.

A particularly promising area is the development of machine learning-based intent recognition within haptic systems. Techniques such as reinforcement learning (RL) and deep neural networks allow robots to interpret human intentions from subtle force inputs or motion patterns, adjusting haptic feedback accordingly. For example, in collaborative assembly tasks, an AI-driven haptic interface could anticipate the human's next action, such as aligning a component, and provide gentle force cues to guide the movement, thereby reducing errors and cognitive load. Recent work by Zhang et al. [48] demonstrates the potential of RL to optimise human–robot collaboration in assembly, while Javdani et al. [12] explore shared autonomy via hindsight optimisation, offering insights into intent recognition for teleoperation and teaming scenarios. Personalisation of haptic feedback represents another critical direction. Individual differences in skill level, physical capability, and preference necessitate tailored haptic sensations. AI algorithms can learn these characteristics over time, adjusting feedback to suit the user. In rehabilitation robotics, for instance, a haptic interface could modulate its guidance based on a patient's recovery progress, providing stronger cues for novices and subtler feedback as proficiency increases [19,49]. Studies on haptic feedback in surgical applications [40] further underscore the potential for personalisation, with AI serving as a key enabler for scaling such adaptations across diverse domains [7].

Stability in teleoperation systems, challenged by communication delays and environmental uncertainties, can also benefit from AI-enhanced predictive control. By modelling human–robot dynamics in real-time, AI can anticipate and compensate for delays, ensuring smooth and stable haptic feedback. Artigas et al. [24] address network-related challenges in teleoperation, while Ghoushkhanehee and Alfi [50] investigate predictive control for bilateral teleoperation with time delays, highlighting the relevance of these approaches for

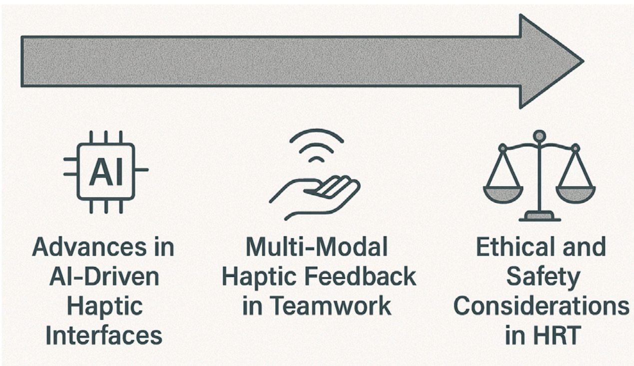


**Fig. 12.** Future areas: AI haptics, multi-modal feedback, and safety in HRT.

remote HRT applications such as space exploration [30]. This stability is vital for maintaining transparency in haptic interactions [2].

Furthermore, generative AI models hold promise for simulating complex haptic sensations, such as interactions with deformable objects or varied textures. Current systems often struggle with these tasks, but generative models could synthesise realistic feedback based on training data, enhancing virtual training environments and teleoperation tasks requiring intricate manipulation. This direction builds on foundational work in cutaneous feedback [6] and aligns with advances in deep learning for sensory simulation [51,52], presenting a fertile area for future research [26].

### *8.2. Multi-modal haptic feedback in teamwork*

The transition of robots into team roles within HRT necessitates a shift beyond reliance on kinesthetic or tactile haptic feedback alone. Future systems will benefit from multi-modal haptic feedback, integrating touch with visual, auditory, and potentially other sensory cues to foster a more intuitive and effective interaction experience. Research in teleoperation has demonstrated the value of feedback in enhancing control [47], and multi-modal systems represent a logical progression for facilitating seamless teamwork.

In scenarios such as search and rescue, a robot could employ vibrotactile cues to alert the human teammate to hazards, such as an unstable structure, while an augmented reality (AR) display provides visual localisation. Pacchierotti's work on cutaneous feedback [6] indicates the efficacy of tactile signals, and their combination with AR could enhance response times and situational awareness. Prewett et al. [53] provide a narrative review of multimodal workload management in human–robot environments and discuss how haptic cues may serve as a useful complement to visual information in demanding tasks, rather than offering quantitative confirmation of performance gains. Additionally, Che et al. [36] report reduced operator workload in a gesture-based teleoperation setting with haptic feedback, further illustrating the practical value of multimodal approaches [27].

Haptic feedback in shared control for multi-agent teams presents another promising direction. In collaborative tasks involving multiple robots and a human, such as transporting a large object, haptic cues could convey the collective state of the team, enabling intuitive adaptation to changes in robot behaviour. Abbink et al. [13] have established a foundation for haptic shared control in automotive contexts, and extending this to HRT could leverage impedance-based models [11] to balance human and robot inputs effectively. Dragan and Srinivasa's work on policy blending for shared autonomy [45] offers additional insights into coordinating control in teaming scenarios [54].

Cross-modal adaptation, where haptic feedback adjusts dynamically based on the reliability of other sensory channels, also holds significant potential. In environments with high visual or auditory noise, amplifying tactile cues can maintain effective communication. An older teleoperation-focused meta-analysis by Nitsch and Färber [16] reported a large overall task-performance effect of haptic feedback (Hedges' $g = 0.96$, 95% CI 0.71–1.21), but also substantial heterogeneity across studies ($Q = 92.75$, $I^2 = 66.6\%$). It is therefore more accurate to interpret that result as evidence that haptic augmentation can be beneficial under some teleoperation conditions, rather than as proof of a uniform multimodal advantage across all HRI settings. Recent studies such as Abbink et al. [55] explore the interplay between visual and haptic feedback in shared control. Integrating AI to optimise this multimodal interplay, informed by principles of sensory integration [56], could further enhance teamwork efficiency [57].

### *8.3. Ethics and safety in HRT applications*

The integration of robots as teammates in HRT necessitates rigorous attention to ethical and safety considerations. The development of stable teleoperation systems has long prioritised safety [23], but HRT introduces additional complexities as robots and humans share both physical and decision-making spaces. Addressing these challenges is essential to ensure that haptic-enabled systems are trustworthy, secure, and ethically sound.

A further motivation for proactive governance is historical precedent: industrial robot safety standards have often followed (rather than preceded) accidents, so AI-adaptive haptic teaming should be accompanied by pre-deployment risk assessment, safety-case style validation, and update mechanisms that do not rely on post-incident learning.

A paramount concern is the transparency of robot actions. For humans to trust robot teammates, they must understand the robot's intentions and decision-making processes. Haptic feedback can serve as a medium for conveying intent, such as applying a gentle force to suggest a safer path, but it must be designed to be intuitive and legible. Banitalebi Dehkordi et al. [22] emphasise the need for explainability in HRT, while Dragan's work on legible motion [44] provides a foundation for designing robot behaviours that are easily interpretable. Future research should focus on refining haptic communication to enhance mutual trust, potentially drawing on insights from explainable AI in robotics [58].

Safety in physical interactions remains a critical priority. In this context, ISO/TS 15066:2016 is more specific than a generic statement that "standards matter": Annex A distinguishes *quasi-static* contact (e.g., clamping/trapping) from *transient* contact (e.g., impact) and provides maximum permissible *pressure* and *force* values for 29 specific body areas grouped into 12 body regions [17,59]. For quasi-static contact, representative maximum permissible pressures range from 110 $N/cm^2$ in sensitive facial areas such as the temple or masticatory region to 300 $N/cm^2$ at the dominant forefinger pad, while representative force limits range from 65 N for the masticatory muscle to 220 N in more robust regions such as the thigh/knee; the standard generally applies a multiplier of 2 when moving from quasi-static to transient limits [17]. The same annex also makes clear that although data are tabulated for the face, skull, and forehead, collaborative contact with those areas is *not permissible* and they should therefore be treated as critical zones in any risk assessment [17].

The advent of AI-driven haptic systems introduces additional ethical considerations. Autonomous adjustments to haptic feedback based on learned behaviour raise questions of accountability and bias. Edgar et al. [46] highlight the potential for bias in AI systems, underscoring the need for ethical frameworks that ensure fairness and transparency. Adapting guidelines from human-AI interaction research [60] and robot ethics [61] could provide a foundation for addressing these challenges in the context of haptic HRT [62].

Furthermore, the biomechanical thresholds in ISO/TS 15066 should be understood in terms of how they were derived. The standard states that the *quasi-static pressure* limits were obtained from a University of Mainz pain-onset study involving 100 healthy adult subjects and

29 specific body areas; the reported values correspond to the 75th percentile of recorded pain-onset pressures measured using a flat $1.4 \times 1.4$ cm metal contactor with 2 mm edge radii [17]. By contrast, the *force* limits were not obtained from that same direct experiment: according to the standard, they were derived by an independent organisation from 188 literature sources using the lowest energy-transfer criterion associated with minor injury (approximately AIS 1), and the transient-contact multipliers were then estimated from prior studies indicating that transient limits can be at least twice the quasi-static values [17,59]. This mixed derivation is important for HRT: these values are best treated as conservative engineering guidance within a structured risk assessment, not as universally validated human injury laws, and later work has explicitly noted that some of the ISO/TS 15066 limits remain preliminary and may need revision as more robot-specific biomechanical evidence becomes available [63].

## 9. Conclusion

The primary synthesis output of this review is the design-space matrix in Table 7. Rather than presenting the paper as a complete design manual, the matrix makes the across interaction modes comparison explicit by linking each mode to five practical design cells: dominant haptic purpose, what the human mainly feels, robot-side enablers, primary design priorities, and typical evaluation focus/main risk. For example, the caged-automation row identifies "productivity and safety by separation" as the dominant design priority, whereas the HRT row identifies legibility, non-coercive assistance, consistent feel across mode changes, and verifiable adaptive safety as the corresponding design priorities for AI-mediated teaming.

In response to RQ1 and RQ2, Table 7 shows that haptic feedback changes both in purpose and in control meaning as human–robot integration deepens. The HRI row frames haptics mainly as remote rendering and command guidance, where the human feels force reflection, kinesthetic resistance, or tactile/vibrotactile alerts, and the central design trade-off is transparency versus stability. The HRC row shifts the same general idea towards shared-workspace contact mediation, where force/torque sensing, impedance with saturation, and collision/contact detection support safe co-location and standards compliance. The pHRC row then moves to sustained force negotiation and load sharing, where direct shared-load feel, admittance/impedance control, and ergonomic tuning become central; finally, the HRT row extends haptics towards intent, confidence, and authority communication through adaptive kinesthetic cues, shared-control feel, and wearable cutaneous/vibrotactile prompts.

In response to RQ3, the evaluation-focus/main-risk column of Table 7 highlights why reproducible benchmarking remains difficult across the interaction modes. HRI studies commonly emphasise task success, transparency, workload, and stability under delay, whereas HRC studies more often report completion time, error, peak/contact forces, and comfort. In pHRC, the important evaluation cells shift towards effort, force variability, comfort, and task quality, with fatigue, instability, and non-intuitive load sharing as key risks. In HRT, Table 7 identifies fluency, trust, mode awareness, and override success as evaluation targets, while mode confusion and over-assistance become major risks; this is also why the evidence-grading summary in Table 8 treats AI-adaptive haptic teaming as emerging rather than mature.

The scope and limitations of the review should also be read through Table 7. The matrix deliberately emphasises force-mediated and physically grounded haptics, including impedance/admittance control, force exchange, contact regulation, and shared-control mechanisms, because these are the clearest cross-stage links between the HRI, HRC, pHRC, and HRT rows. Tactile, cutaneous, and vibrotactile modalities are included where they materially support the "what the human mainly feels" and "dominant haptic purpose" cells, but the paper is not intended as an exhaustive review of tactile display design or haptic psychophysics [6,7]. Similarly, the retained one-degree-of-freedom expressions are simplified abstractions used only to support the interpretation behind the matrix and Table 6, not to provide design-ready controllers. The review therefore leaves open the practical challenge identified most clearly in the HRT row of Table 7: developing adaptive haptic cues that remain legible, trustworthy, non-coercive, and verifiably safe across changing users, tasks, and autonomy levels.

## CRediT authorship contribution statement

**Aghil Jafari:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Muhammad Hamza Zafar:** Validation, Methodology. **Filippo Sanfilippo:** Supervision.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Aghil Jafari reports financial support was provided by Engineering and Physical Sciences Research Council. Filippo Sanfilippo reports financial support was provided by Artificial Intelligence, Biomechatronics, and Collaborative Robotics research group. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

No data was used for the research described in the article.

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