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Review article

Sensory substitution increases robotic surgical performance and sets the ground for a mediating role of the sense of embodiment: a systematic review

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ABSTRACT

Sensory Substitution (SS) allows the elaboration of information via non preferential sensory modalities. This phenomenon occurs in robotic-assisted surgery (RAS), in which haptic feedback is lacking. It has been suggested that SS could sustain surgeons' proficiency by means of visual clues for inferring tactile information, that also promotes the feeling of haptic phantom sensations. A critical role in reaching a good performance in procedural tasks is also sustained by the Sense of Embodiment (SE), that is, the capacity to integrate objects into subjective bodily self-representation. As SE is enhanced by haptic sensations, we hypothesize a role of SS in promoting SE in RAS. Accordingly, the goal of this systematic review is to summarize the evidence pertaining the study of SS in RAS in order to highlight the impact on the performance, and to identify a mediating role of the SE in increasing dexterity in RAS.

Eight studies selected from the MEDLINE and Scopus® databases met inclusion criteria for a qualitative synthesis. Results indicated that haptic to other modalities SS enhanced force consistency and accuracy, and decreased surgeon fatigue. Expert surgeons, as compared to novices, showed a better natural SS processing, testified by a proficient performance with and without SS aids. No studies investigated the mediating role of SE. These findings indicate that SS is subjected to learning and memory processes that help surgeons to rapidly derive haptic-correlates from visual clues, which are highly required for a good performance. Also, the higher ability of doing SS and the associated perception of haptic sensations might increase multisensory integration, which might sustain performance.

1. Introduction

Although we are subjected to a constant stream of sensory inputs, our perception continuously operates by processes of selection and organization. The mechanisms behind perception involve the association between stimuli coming from different sensory modalities resulting in multisensory stimulation. However, under certain circumstances, multisensory stimulation could be prevented, thus spurring humans to detect the characteristics of stimuli from the available sensory modalities: for example, it is possible to infer the stiffness of a fabric (usually detected via tactile exploration) from visual clues. These phenomena are collectively named Sensory Substitution (SS), defined as the transformation of stimulus' characteristic of one sensory modality (for example, vision) into stimuli of

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another (for example, touch) [1]. Or, within the same sensory modality, when different receptors are targeted (for example vibrotactile modality for presenting force feedback information) [2].

As such, SS is helpful during conditions that limit the access to a preferential sensory modality; indeed, typical examples in which SS is important are all cases in which an individual suffers from a sensory impairment (e.g., blindness, amputation). For example, in the case of blindness, visual information can be presented through auditory or tactile modality by converting properties of vision (luminance, vertical and horizontal positions) into auditory (e.g. amplitude, frequency) or tactile properties (e.g. intensity) [3–5]: as a result, impaired individuals using SS devices are able to compensate the loss of sensory functions.

Consequently, several SS devices have been employed for sensory impairments

- In the field of visual impairment, for example, "The vOICe" is a visual-to-auditory SS device that transforms live camera feed into sonifications [6]. For what concern SS devices that use visual to tactile SS, the Tongue Display Unit that delivers electrotactile (electrocutaneous) stimulation on the anterior-dorsal tongue stimulation through a matrix of surface electrodes [7];

- In the field of amputation and prosthetics, haptic SS devices have been successfully implemented, since they allow participants the comprehension of the position of an artificial limb [8]. Regarding prosthetics (upper limbs), sensory feedbacks have been provided by means of haptic SS devices: for example, Cipriani et al. [9], used a SS system based on miniaturized vibration motors able to generate stimuli capable of modulating both vibration amplitude and frequency as well as beat interference. Some SS devices for upper limb amputees deliver electrotactile stimulation instead of vibrotactile stimulation, such as the wearable prototype transmitting the acquired tactile information to the prosthetic user through electrotactile stimulation [10].

In addition to human sensory impairments, SS can be considered a workaround when sensory deficits are caused by limits in present technology that temporally (but not irreversibly) prevent the access of the preferential sensory modality, thanks to which a particular action is performed: a typical example of SS is given by the interface between humans and computers [11]. This is the case when an action is operated remotely and/or through devices that allow for increased force or more fine-tuned movements (telemanipulated), such as articulated arms (for teleoperators, bulldozer operators), or robotic arms (surgeons).

In the context of telemanipulation, some learning phenomena occur to compensate for a temporary sensory lacking and to guarantee a proficient performance [3–5]. In this context, SS occurs when the transmission of environmental information is given by recruiting another sensory channel rather than directly obtaining kinesthetic haptic feedback from the master site. Typically, haptic feedback (HF) is substituted with visual or auditory and tactile displays [12]: this compensation, however, occurs via devices providing visual, auditory, tactile signals, thus making the substitution connoted as 'artificial'.

Herein, we introduce the concept of 'natural SS', that would share the same cross-modal transfer physiological mechanisms of the artificial SS (by which the recognition of an object occurs thanks to an experienced-based learning involving sensory cortices in processing sensations other than their usual one [13,14]), but that occurs without artificial feedbacks.

A typical example in which natural SS might occur is the robotic-assisted surgery, which, differently from open surgery, prevents the availability of haptic clues, and impedes to experience the environment through active exploration, typically with the hands, through processes of palpation and manipulation [15]. In fact, the active palpation and manipulation usually done directly with surgeons' hands is substituted by stick-like metallic instruments that literally become "the new arm of the surgeons". By means of these tools, robotic assisted surgery systems allow tremor reduction, motion scaling, and wrist movements [16] while delivering high-quality, magnified, surgeon-controlled 3-dimensional, stable images [16–18].

Despite the numerous potentials of robotic surgery, the lack of HF is reputed to be among reasons why the spread of surgical robots is limited. The introduction of HF has been found to be pivotal for several surgical skills, such as the enhancement of force consistency, improvement of patient safety and the decrease of surgeon fatigue during operation) [19]: this is particularly true for novice surgeons, since they claim that it would improve learning and decrease the workload during robotic training (especially in the early phases) [12].

However, it has been found that the use of HF, such as external force feedback, could also be detrimental, as stated in a recent review "In a teleoperation, the closed-loop that controls the interactions between the master, the robot and the remote environment is a key feature, and the stability of this closed-loop is essential, considering the nature of the application where any instability can be detrimental" [20]. To mitigate this instability, and thus enhancing surgical performance, artificial SS has been employed: for example, visual feedback to convey interaction forces to surgeons [21–24], visual and auditory cues to provide a representation of applying forces [22].

In absence of artificial devices to convey haptic information, lack of HF forces surgeons to use visual cues for inferring information like pressure and force, in order to recognize membranes and tissues. Indeed, after the earliest phase of training, "nonhaptic perceptual substitutes compensate for the lack of discriminatory force, tactile cognizance, and mechanical arm proprioception", thus creating a subjective perception of HF that obviates its absence [18,25]. In other words, with experience, the surgeon at the control console of these systems "learns" subconsciously to translate visual information into tactile one, and this information is used during surgical procedures, and a natural SS might occurs.

SS could also sustain surgeons' proficiency in an indirect way: in fact, "phantom haptic perception" or the trasduction of haptic sensations by SS devices perceived by robotic surgeons could also increase the confidence toward the robotic arm, which is mainly sustained by the Sense of Embodiment (SE). SE is the capacity of "experiencing the body as belonging to themselves and being able to integrate objects into subjective bodily self-representation" [26]. It comprises three components: sense of self-location, that is the feeling of location in space; the sense of ownership, that is the feeling that non-bodily objects are part of one's own body; the sense of agency, that is the feeling of being the author of an observed action of (motor) control [27,28].

When performing complex tasks with a telemanipulator, individuals should have the impression of physically being at the point of interaction, so that the interaction itself feels as natural and intuitive as possible (and thus increasing the sense of telepresence, the feeling of being present at another location than the physical location of one's body [28]. As a result, increased experienced SE can enhance performance [28] because, once established, embodiment can reduce the susceptibility of individuals to inconsistencies in the size, movements, degrees of freedom, etc., of the teleoperated device.

In summary, a possible positive role of the SS and of the SE in improving dexterous performance have been suggested, and a role of SS in promoting the SE in telemanipulated environments can be hypothesized. Accordingly, the goal of this systematic review is to summarize the evidence regarding the study of SS (natural and artificial), in order to highlight the impact on the performance, and to identify a mediating role of the SE in increasing dexterity. For the study, we limit the search of investigation to the following fields:

- robotic-assisted surgery, since it requires both to operate via artificial arms (robotic effectors) and to view through an immersive visor: this setting imposes surgeons to be (tele)present despite the physical distance from the operating table;
- haptic to other sensory modalities natural and artificial SS, since robotic surgeons are required to compensate for the lack of haptic information (tactile haptic and kinesthetic haptic, mainly via visual cues during surgical procedures).

2. Materials and methods

A systematic review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [29] (Supplementary Table 1).

The search strategy was developed following the Population, Intervention, Comparison, Outcomes and Study Design (PICOS) worksheet [29] as summarized in Supplementary Table 2.

The three phases of our systematic review process are summarized in the PRISMA flow diagram (Fig. 1).

1- (Identification phase): an initial electronic search was performed, based on queries applied to scientific literature databases MEDLINE and Scopus®. The database search comprised papers published from database inception to August 2023. The queries contained keywords relating to SS, robotic surgery and embodiment. Full search terms are displayed in Supplementary Table 3. The search results were merged after deleting duplicates using the Mendeley desktop reference manager (http://www.mendeley.com).

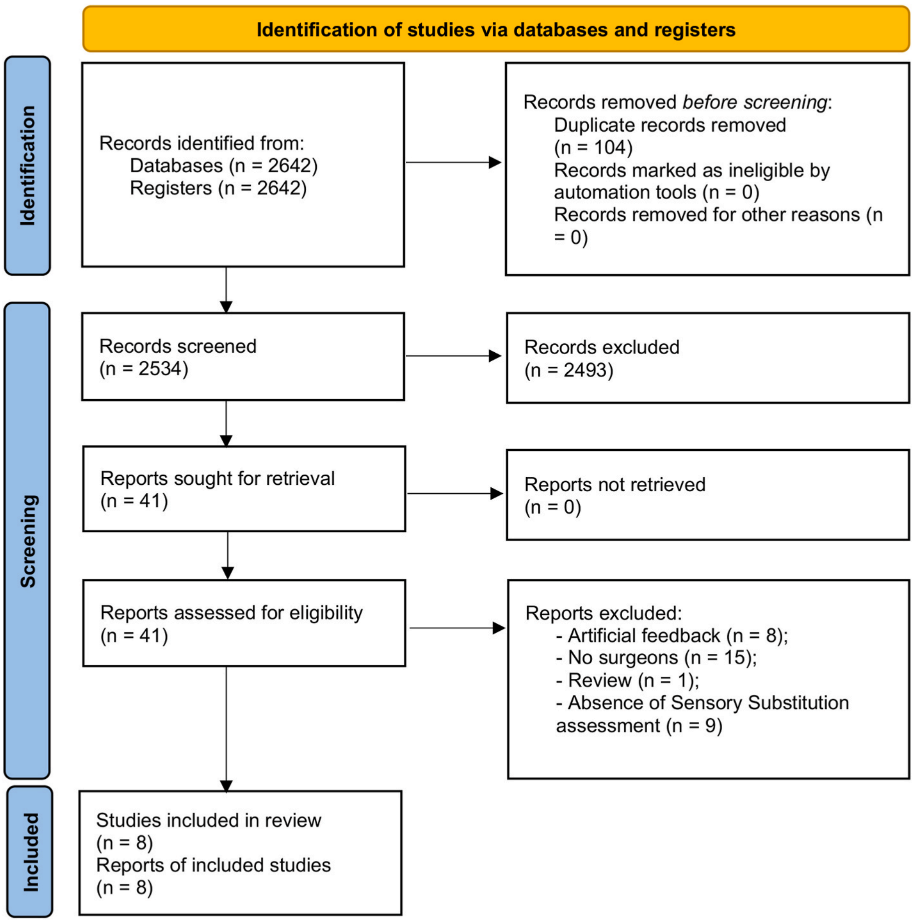

Fig. 1. Diagram of study selection.

Table 1
Main outcomes of natural SS studies.

Authors	Objectives	Number of participants	Design	Sensory substitution	Experimental procedures	Behavioral and psychometric outcomes	Main findings
Cundy et al., 2014 [30]	To explore the effect of surgeon experience in overcoming HF loss in robotic surgery	1 surgeon	Within subject	Haptic to visual (natural Sensory Substitution)	The patient cohort was separated into sequential quartile subgroups to determine the effect of surgeon experience	Suture damage frequency, size and robotic instruments used for suturing were subjected to post hoc analysis	The overall frequency of suture damage was 2,5 % among 1135 sutures used in 52 patients; a significant inverse relationship between surgeon experience and suture damage frequency was identified; surgeon experience was associated with shorter operative times
Hagen et al., 2008 [25]	To demonstrate that visual clues in robotic surgery can compensate for the lack of HF, making these less important	Total surgeons = 52 - Novices = 34; -Intermediates = 8 - Experts = 10	Between subject	Haptic to visual (natural Sensory Substitution)	The first group was asked to complete 3 different tasks, with different difficulty levels; All groups were asked to complete a questionnaire on the perception of HF during robotic surgery; all questions were answered with a visual analog scale of 1 (= not at all) to 10 (=very much)	Perception of HF during robotic operations; How much HF was missed during robotic operations; How much the lack of HF impaired the operators' level of comfort	50 % of the novices reported the perception of HF; 50 % of the Intermediates reported the experience of HF during robotic operations, while the 100 % of the experts reported that experience; difference between novices + intermediates and experts. The novices missed the HF for 6.5; the intermediates missed HF for 4.3 and the experts for 4; the difference between novices and experts was significant. experts reported to have missed HF for 7.2 when they first started robotic surgery (difference to now: significant). The discomfort for lack of HF was rated 4 for the novices , for the intermediates was rated 4, and for the experts 2.6 (all differences not significant)
Meccariello et al., 2015 [31]	To demonstrate that the experience of the surgeon is sufficient to compensate for the lack of HF in robotic surgery	Total surgeons = 25; - Novices = 19; - Experts = 6	Between subject	Haptic to visual (natural Sensory Substitution)	Each subject was presented 3 synthetic membranes; surgeons had to indicate in descending order the thickness of each membrane and the position of the metallic clip in the	Overall performance in the tasks, completion time, perfect sorting, correct identification of the clip, opinion about the necessity of a force feedback sensor	Expert surgeons achieved a significant higher score compared to non-experts; Time spent to complete the task by experts was lower than non-experts; 67 % of experts correctly identified

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Table 2
Main outcomes of artificial SS studies.

Authors	Objectives	Number of participants	Design	Sensory substitution	Experimental procedures	Behavioral and psychometric outcomes	Main findings
Aviles-Rivero et al., 2018 [24]	To demonstrate the potential benefits of using this modality and to comprehend the surgeons' perceptual preferences	Total surgeons = 28 - Experts = 9 - Novices = 19	Mixed (between and within subject)	Type of SS: haptic to visual Tools: force feedback by means of circles, bars, heat map, traffic light	Participants were provided four visualization modalities (a = circles, b = bars, c = heat map, d = traffic light) during a video in which interaction was passive (users watched the prerecorded video demonstrating tool-use interaction, with one of the four visualization systems being overlaid on the video to convey information about the force applied in the video corresponding computer-based questionnaire in order to answer to questionnaire)	- Perceived usefulness: the degree to which participants believe in SS devices for performance improvement - Learnability: the indication of how easy it is to accomplish basic tasks and interpret outputs of a system. - Perceptual limitation: the degree to which participants are able to respond to changes in each one of these systems by means of their sensory system. - Consistency: the level of logical relation between input-output of the system - Satisfaction: participants' level of comfort and acceptability of the proposed system.	No statistically significant differences between experts and novices as defined in this study for any of the considered factors. Surgeons expressed the strongest preference for Systems A and D (70 %) in terms of perceived usefulness. There was a clear rejection of System C by both groups as compared to the rating of systems A, B, D
Bethea et al., 2004 [21]	To verify whether HF, in the form of sensory substitution, facilitates the performance of surgical knot tying.	5 surgeons	Within subject	Type of SS: haptic to visual Tool: visual color bar scale to render applied suture tensions	Knot tying with visual sensory substitution and without visual sensory substitution. The surgeons were instructed to either increase or decrease the amount of tension applied to the suture (Four Different Suture Types: Ti-Cron 2-0; 5–0 polypropylene; 6–0 polypropylene; 7–0 polypropylene) to maintain the color bar in the green zone.	Applied tension	-Ti-Cron group: the mean tension applied was significantly lower with visual sensory substitution; - polypropylene groups: mean tensions applied to fine polypropylene sutures were greater with each type of suture when HF was applied (near significant in the 6–0 polypropylene group; significant in 7–0 polypropylene group)
Kitagawa et al., 2005 [22]	To study the effects of substituting HF with visual and auditory cues to provide the operating surgeon with a representation of the applying forces	5 surgeons	Within subject	Type of SS: haptic to visual, haptic to auditory; haptic to visual-auditory Tools: - visual: a graphic display of the force levels by means of color bars; - auditory: a single tone when the magnitude of the applied tension reached the manual tension	Comparison of applied forces during a standardized surgical knot-tying task on different suture materials (Silk 2-0; TI-CRON 2-0; Polypropylene; 4-0 Polypropylene; Polypropylene 5-0; Polypropylene 6-0; Polypropylene 7-0) under ideal condition (tensions incurred with manual ties) and 4 different sensory-substitution scenarios: no feedback, auditory feedback, visual feedback, and combined auditory-visual feedback	Coefficient of variance (force consistency); mean of applied forces	The means of applied force with these sensory-substitution aids more closely approximated suture tensions achieved under hand ties with respect to forces applied without sensory substitution. The consistency of applied forces during robot-assisted suture tying aided by visual feedback or combined auditory-visual feedback sensory substitution was superior to that achieved with hand ties. Robot-assisted ties aided with auditory feedback revealed levels of consistency that were generally equivalent or superior to

(continued on next page)

Table 2 (*continued*)

Authors	Objectives	Number of participants	Design	Sensory substitution	Experimental procedures	Behavioral and psychometric outcomes	Main findings
							those attained with hand ties. Visual feedback and auditory feedback improved the consistency of robotically applied forces
Mayer et al., 2007 [32]	To evaluate of the impact of force measurement and feedback on surgical procedures.	Total surgeons = 28 Novices = 8 Experts = 12 Robotic surgeons = 5	Mixed (between and within subject)	Type of SS: haptic to haptic (force feedback) Tool: strain-gauge sensors with 2 levels of amplification	Knot-tying, breaking, and detecting stenosis in three conditions: no feedback; feedback with real measured forces; amplified force feedback	Mean force during knot-tying; differences between indicated and actual force during breaking; error in detection during stenosis; performance time progression of surgeon's fatigue	The amplification of force-feedback led to a significant decrease of applied forces. The difference between the assumed and the real force during suture breaking significantly decreased with amplitude of HF. HF had no significant influence on detection errors and performance time. The use of HF led to a significant decrease of fatigue
Reiley et al., 2008 [23]	To study the effects of visual force feedback performance of surgical knot tying	Total surgeons = 10 - Experts = 4; - Novices = 6	Mixed (within and between subject)	Type of SS: haptic to visual Tool: Force display consists of two semi-transparent circles superimposed over the corresponding instrument tips as they move freely in space to haptic	The surgical task consisted in 20 knot-tying trials, 10 with visual force feedback and 10 without. All surgeons were instructed to tighten the knot by (1) grasping the suture with the two forceps close to the knot and (2) pulling the suture laterally in the plane of the task board	Instrument/environment bending forces, instrument tip position, suture breakage, knot security (i.e., secure versus loose knots), and task completion time. Qualitative survey to assess whether or not visual force feedback was preferred and the reason(s) for the preference	Among surgeon with robotic experience, no differences in measured performance parameters were found between robot-assisted knot ties executed with and without visual force feedback. Among surgeons without robotic experience, however, visual force feedback was associated with lower suture breakage rates, peak applied forces, and standard deviations of applied forces. Visual force feedback did not impart differences in knot completion times or loose knots for either surgeon group. Visual force feedback was preferred by all subjects during the knot-tying trials largely due to the confidence it conferred in avoiding excessive applied forces while ensuring a secure knot

Table 1 (*continued*)

Authors	Objectives	Number of participants	Design	Sensory substitution	Experimental procedures	Behavioral and psychometric outcomes	Main findings
					thinner membrane; they also had to express their opinion about the necessity of introduction of a force sensor in the Da Vinci system		the metal clip compared to non-experts; 67 % of experts correctly sorted the membranes compared to 47 % of non-experts; 78,9 % of non-experts expressed the need of introduction of a force sensor in the surgical system compared to 16,4 % of expert surgeons

2- (Screening phase): the retrieved articles were manually screened against a priori defined inclusion/exclusion criteria (Supplementary Table 2). Inclusion criteria incorporated studies with: participants engaged in robotic assisted surgery; artificial or natural haptic to other sensory modalities SS; behavioral outcomes (such as number of errors, time completion; applied force) retrieved from real surgical procedures or from simulated procedures (e.g., training at surgical console); evaluation of SS (for example, by means of questionnaires or behavioral measures).

3- (Eligibility phase): a full-text in-depth assessment of the remaining papers was finally conducted.

Supplementary Table 2 summarizes the three search steps performed for each database and Supplementary Table 3 shows the final query for both MEDLINE and SCOPUS.

Two independent reviewers (V.C. and F.M) and one referee (D.M) were involved in all the above-mentioned processes (data sources and search strategy, procedure for studies selection, quality assessment and data extraction). Any disagreements were resolved by reaching a consensus between the authors.

3. Results

3.1. Study selection and characteristics

The search process for each database is presented in Supplementary Table 3. The articles found in the PubMed and Scopus databases were merged into a list of 2534 papers. This initial pool was screened for conformity with inclusion criteria, resulting in a final list of 8 papers for qualitative synthesis, globally encompassing data gathered from 154 subjects (Fig. 1).

Of these studies, 3 investigated natural SS [25,30,31], whereas 5 investigated artificial SS [21–24,32].

3.2. Synthesis of the main findings

Herein, we provided a synthesis of the main findings according to the grouping performed by taking into account the investigation of SS type (Natural SS and Artificial SS).

3.2.1. Natural SS

Three studies investigated the role of natural SS (the role of visual clues in compensating the lack of HF) on behavioral indices (e.g., elapse time, number of errors), self-report measure of benefits derived from the introduction of SS aids (e.g., likeability, perceived usefulness) taking into account the level of experience.

Hagen and colleagues [25] demonstrated, for the first time, that visual clues in robotic surgery can compensate for the lack of HF. The authors surveyed 52 surgeons on their perception of HF during robotic surgery by dividing the sample into 3 groups: surgically inexperienced individuals; laparoscopic surgeons with medium experience; expert robotic surgeons. Subjects underwent a visual analog assessment about the perception of HF, how much HF was missed, and how much the absence of HF impaired the their level of comfort. Robotic experts were asked if complications had occurred because of a lack of HF. Results showed that expert surgeons, as compared to inexperienced ones, have the ability to feel haptic sensations during operations (100 % of expert vs 50 % of inexperienced), they are less likely to miss feedback, and they showed a lower degree of discomfort when HF was absent. Also, robotic-assisted expert surgeons declared to have missed HF more when they first started robotic surgery with respect to the moment in which they had been interviewed (Table 1).

Another work significantly contributing to the field is that of Cundy and colleagues [30], who longitudinally studied a single surgeon's learning curve, which involved a study cohort of 52 patients, for a total of 1135 sutures. Authors found an inverse relationship between experience and suture damage frequency as well as shorter operative times (Table 1). This has been ascribed to an acquired compensatory sensory mechanisms that might occur in surgeons.

In the third paper, similarly to Hagen et al. [25], Meccariello and colleagues [31] conducted a study to verify whether surgeons' experience could counteract the absence of HF in robotic surgery via visual clues in a task in which surgeons were asked to identify the consistency of 3 synthetic membranes just by using vision. Also, surgeons were asked about the opportunity to introduce HF for a better performance during tasks. At the consistency task, expert surgeons achieved a higher score compared with non-experts, and the completion time was significantly lower in experts with respect to non-experts. Also, only 16.4 % of experts surgeons declared itself in favor regarding the introduction of the force sensor, compared to 78.9 % of non-experts (Table 1).

As a summary, the 3 studies coherently highlighted the role of SS in performing surgery with robotic devices, but none of them investigated the role of embodiment as a mediating factor on the performance.

3.2.2. *Artificial SS*

Five studies investigated the role of artificial SS providing force feedback information via visual [21–24], auditory [22], mixed visual and auditory [22], and haptic cues [32] to study the effects on behavioral indices (e.g., elapse time, number of errors), physical indices (e.g., applied force, force consistency), self-report measure of benefits derived from the introduction of SS aids (e.g., likeability, perceived usefulness).

The study performed by Aviles-Rivero and colleagues [24] used a visual feedback to convey force feedback by means of four different presentations of visual cues in surgeons with different level of experience (novices and experts). The different visual cues allowed to study visual SS as potential tools by which surgeons can benefit from. They also allowed to research surgeons' perceptual preferences among visualized force feedback information in the form of circles, bars, heat map, and traffic light. Surgeons were asked to express perceptual preferences by means of a self-report questionnaire presented after a pre-recorded video projection demonstrating tool-use interaction, with one of the four different visual force feedback conveying cues being overlaid on the video. Results showed no differences between experts and novices regarding the usability and reliability of the SS interfaces. In fact, all surgeons expressed the strongest preference for circle and traffic light in terms of perceived benefits (70 %), and the heat map as the lower rated visual modality (Table 2).

The same haptic to visual modality substitution in experts and novices has been performed by Reiley et al. [23], that employed a display showing two circles conveying force information over the robotic arms' tips during movements to study the beneficial effects of this aid during a knot tying task. Performance indices (instrument/environment bending forces, instrument tip position, suture breakage, knot security) and qualitative assessment were studied in trials with and without SS aid. At the same time, perceived benefits of visual force feedback were collected in the form of qualitative survey. Results showed that, among expert surgeons, the performance parameters did not differ between trials executed with and without visual force feedback. Instead, novices using visual force feedback showed better performance indices, with the exception of completion time. Moreover, both experts and novices expressed the preference for visual force feedback, since it helps to regulate force and, at the same time, it guarantees a secure knot (Table 2).

Similarly, Bethea et al. [21] studied the potential of haptic to visual SS in the form of visual color bar scale, by rending applied suture tensions in performing a knot tying task using four differences suture material types. For all the material types, the applied tension to the suture was significantly more consistent with the aid of visual force feedback, as compared to the performance reached without aid (Table 2).

Compared to previous studies investigating a single modality of SS, the work of Kitagawa et al. [22] employed three different types of SS: haptic to visual (by means of color bar showing force level), haptic to auditory (by means of the delivering of single tone when the magnitude of the applied tension reached the manual tension), and haptic to visual-auditory, (involving both the aforementioned SS types). Surgeons were asked to perform knot-tying trials with each SS aid type (total = 4 conditions), and also hand tied trials (ideal HF). The mean of applied force was extracted to verify the approximation of suture tension with and without SS aids to hand ties sutures, whereas the coefficient of variance estimated force consistency in all conditions. Results showed that the force applied with SS aids was close to that reached during hand ties (ideal HF conditions), as compared to conditions without aids. In visual and visual + auditory SS, the consistency of applied force was higher than hands ties, and auditory SS showed equivalent or higher consistency of applied force as compared to those obtained by hand ties. Visual feedback and auditory feedback improved the consistency of robotically applied forces (Table 2).

Differently from previous studies, Mayer et al. [32] employed a haptic to haptic SS by means of strain-gauge sensors providing force feedback, in a group of surgeons with different levels of experience. Participants were required to perform a knot-tying task and a stenosis detection task in three conditions: absence of feedback; feedback with real-measured forces; amplified force feedback. Results showed that the amplified feedback led to a significant decrease of applied force and a decrease of the differences between the expected and real force during suture breaking. The introduction of HF did not impact on detection errors or performance times, whereas it positively impacted on the surgeons' fatigue, by significantly decreasing it (Table 2).

In summary, these 5 studies coherently highlighted the role of SS in performing surgery with robotic devices, but none of them investigated the role of embodiment as a mediating factor on the performance.

4. Discussion

The current review investigated the ability of surgeons to take advantage of SS – a process by which a sensory modality is engaged to elaborate information normally processed by other sensory modalities – during surgery to compensate for the lack of HF, and the possible role of embodiment in enhancing professional performance via SS. Here we have connoted as 'natural' the SS that occurs without any types of aids, and 'artificial' the SS that occurs via SS devices.

4.1. Sensory substitution might be subjected to a "learning-memory" process for enhancing performance

In the robotic surgical field, the lack of HF is an important issue that surgeons, in particular the novices, complain about, since it forces them to use other sensory modalities (mainly visual) to infer information such as pressure to be applied with scalpels, tissues/membranes to be recognized, and so on.

At present, only 8 experimental papers [21–25,30–32] have engaged with this issue. From the studies regarding natural SS, emerges a tangible difference within the surgeons when experience is considered (experts vs novices). In fact, experts displayed better performance (in terms of speed, spatial accuracy and material recognition). In addition, they were able to feel "phantom" haptic sensations during procedures, and were less prone to request HF.

All these outcomes suggest that visual clues substitute haptic sensations even if they are just temporarily prevented, that is a process that might be driven by SS. Importantly, the capacity of doing SS without aids appears to be higher in expert surgeons: this could be ascribable to their greater capacity of using visual clues, intimately related to the number of surgical operations performed.

Regarding the use of artificial SS, it appears that SS devices have a positive impact on the performance of surgeons during tasks [21–24,32]. The studies report a decrease in applied forces and an improved consistency during procedures [21,22,32], indicating that SS possesses quantifiable advantages in accuracy and consistency of the applied force, and HF in the substituted form is useful for surgical tasks, since surgeons applied less force. Moreover, some studies found that surgeons are prone to rate the aid of SS in a positive manner: the use of HF led to a significant decrease of fatigue in the study of Mayers and colleagues [32], while the study by Reiley and colleagues [23] highlighted that visual force feedback was preferred due to the confidence it conferred in avoiding excessive applied forces while ensuring a secure knot.

The process of SS (both natural and artificial) is subjected to learning, and it has been found to improve with experience [3,5]. Since SS has been proposed as a form of artificial synaesthesia due to the induction of some form of conscious concurrent experience or the presence of patterns of crossmodal interference, both characterizing synaesthesia, the condition in which individuals experience a percept in one sensory or cognitive pathway when another one is stimulated (e.g., perceiving colors while hearing a music) [13,33,34], it is important to pointing out the differences between two phenomena: synaesthesia is a totally involuntary process, and it is not subjected to any type of learning, while SS is sensitive to training [13].

The role of experience seems to be particularly evident in the study of Cundy and colleagues [30], in which authors analyzed data from a single surgeon's experience, captured all along his learning curve. In this work, authors highlighted an inverse relationship between experience and suture damage frequency and a positive association between experience and shorter operative times. Also, in the work of Reiley et al. [23], differences emerged between expert and novice surgeons: in fact, experts did not show differences in performance indices with the introduction of visual force feedbacks, whereas novices did. The difference between the two groups could be ascribed to the natural SS that expert surgeons might employ during procedures, that could help them to visually compensate for haptic modality even without additional devices.

Another expected hallmark of SS is the formation of sensory memories regarding the substituted modality. For example, in the case of natural SS, expert surgeons report "phantom" haptic sensations that might guide them during procedures, and "phantom" haptic sensations are known to be stored in detailed, durable long-term memory representations like genuine products of haptic perception [25,35]. Moreover, the formation of sensory memories for haptic sensation could be enhanced with artificial SS aids by means of a process of facilitation of haptic experiences. For example, the work of Pasqualotto et al. [36] found that visual information improves haptic memories. In this line, analogously to the role of sensory memories in genuine perception, haptic long-term memory representations are strategically retrieved to differentiate between visually-presented objects, as well as visual object representations are automatically coactivated and stored when objects are haptically explored [37,38].

In summary, it is possible to attribute the increased ability of doing SS to a brain plasticity process (learning and memory of haptic sensations) that help expert surgeons to rapidly identify haptic-correlates (force, pressure, recognizing membranes) which are mandatory for a good performance.

4.2. The perception of haptic feedback might increase the performance thanks to a multisensory-integrated environment

As reported by Hagen et al. [25], non-expert surgeons (novices) missed the perception of HF more than surgeons with substantial experience in robotic surgery. Perceived lack of HF is associated with a certain amount of discomfort for the robotic surgeon, whereas the perception of HF increases with professional experience. Similarly, Reiley et al. [23] found no differences in performance indices between expert surgeons when visual force feedback is delivered, thus highlighting a possible acquired visual compensation without aids. The enhanced performance acquired by expert surgeons might also be the indirect results of the mediating effect of multisensory integration, evoked by the perceived phantom haptic sensation in natural SS and via the facilitation effects of SS aids.

Regarding natural SS, this perceived or mediated sensation could be evoked via haptic imagery of this sensory component, that has been previously consolidated through experiences. In fact, it has been suggested that haptic imagery can lead to perceptions of physical control, which in turn increase feelings of ownership, and the intensity of these feelings are directly proportional to the vividness of haptic image. It has also been found that individuals performing haptic imagery experience a level of perceived ownership similar to that of individuals really touching the object. In fact, as proposed by Klatzky, Lederman, and Matula [39], the power of haptic imagery in perceiving haptic sensation is subordinate to two principles:

- haptic imagery and real touch should share the same or similar function. In this case, it could include functional equivalence between imagery and perception (the proposition that imagery, although it does not result from stimulation of sense organs, is essentially the same as perception in the way that it functions) and the possibility that clear haptic imagery may be a cue for the retrieval of associated information [40,41];

- information conveyed by haptic imagery should correspond in content to information extracted by touch (e.g., similar attributes regarding oftness, texture, weight, and texture should be present also in imagery modality).

Haptic imagery could produce a similar evoked by real HF, thus possibly compensating for its lacking in the field of robotic surgery.

Moreover, it has been found that visual and auditory cues can be employed as facilitators for haptic experiences of virtual objects in virtual reality [42]. This could explain the better performance and/or the consistency and the decrement of applied forces in studies employing artificial SS [21–23,32].

Haptic sensations in the form of haptic imagery and haptic to other modalities substitution could participate in the process of multisensory integration. In the field of tele-operation, it has been remarked the cardinal role of haptic information for multisensory integration, both in the classical tool-use studies and in the domain of robotic tools [43]. Multisensory integration refers to the integrating process involving all senses. This starts with detection of sensory input by modality-specific receptors that translate stimuli (light, sound, chemical, mechanical and temperature) into neural activity. The resulting mental impression of distal stimuli is perceived as a confluent whole: the “percept”. The different stimuli are mentally integrated, thus originating the so-called percept: when this integration is compromised, the perceptive incoherence arises. Perceptive incoherence is defined as a phenomenon induced “by contradictory sensory input or extreme imbalance between various types of sensory input, which result from local or generalized decreased somatosensory feedback or sensory–motor contradictions to such an extent that information cannot be united as one percept. It has been demonstrated that incoherent sensory information brings forth incoherent experiences." [44]. Multisensory integration appears to drive the sense of telepresence (pivotal in tele operation) and the sense of Flow [45], that are essential to reach dexterity in tele operated environments: the first corresponds to the feeling of being present at another location than the physical location of one’s body [46] the second to an experience in which individuals get into an absorption state during a particular activity, while the mind becomes effortlessly focused and engaged [47]. Based on these premises, it is possible to speculate that haptic sensation, in the form of haptic imagery, and in the form of haptic substituted modalities, might increase the multisensory integration similar to real perceived HF. Multisensory integration appears to be an important process in sustaining subjective performance, especially during more demanding tasks.

Despite the aforementioned studies have not directly investigated multisensory integration, a possible role of it might be inferred. Although multisensory integration appears to be central for the sense of embodiment (SE), its role in mediating between SS and performance remains poorly understood.

5. Limitations and conclusions

The current work has the major limitation in the small pool of included studies (N = 8) that impedes robust qualitative conclusions. Other issues concern heterogeneity of the works, that prevent a meta-analytic study (3 used natural SS and 5 artificial SS). Additionally, the outcomes reported for each study showed a low degree of replicability, since mainly based on self-report and non-standardized questions. Importantly, none of the included studies investigated the role of SE in mediating the effect between SS and performance.

Despite the aforementioned limitations, it is possible to hypothesize that both natural and artificial SS can enhance surgeons’ performance thanks to a brain plasticity process (learning and memory of haptic sensations) that helps expert surgeons to rapidly identify haptic-correlates (force, pressure, recognizing membranes) which are mandatory for a good performance. Moreover, SS might allow robotic surgeons to overcome the lack of HF which, in turn, might promote a multisensory integration process. For what concern SE, none of the studies investigated its potential role in robotic surgery, but since it could be argued that haptic sensation increases the multisensory integration in tele operation settings, which, in turn, might enhance SE, a possible role of the SE in foster surgical performance could be cautiously proposed. According to the work of Toet et al. [28], the role of SE in enhancing performance in teleoperation setting could be proposed, as the higher the experienced SE of a remote manipulator (robotic arm), the better the dexterous performance: in fact, individuals have the feeling that are in total control during human-telemanipulation system interaction, and the interaction became maximally natural and intuitive. Although the association between the embodiment and task performance has been poorly studied, some studies have suggested that the SE favors the enhancement of performance in the following clinical/non clinical context: motor learning using a virtual limb in perceptual decision-making task [48], control of prosthesis [49], prosthetic object discrimination and manipulation [50], and prosthetic manual accuracy and sensitivity [51].

These innovative perspectives might help in designing personalized educational training for surgeons – but also for those individuals that operate through tele-manipulation systems – in order to favor the natural and intuitive interaction with the robotic arms (becoming “the new arm of the surgeons”), instead of the mere introduction of HF within the robotic console to face this lacking that has also been found to exert a possible detrimental effects on the close-loop system (interaction between the master, the robot and the remote environment) [20].

Moreover, this review might constitute a primer for a future experimental design to study in-depth the relationship between SS, the SE, and task performance.

An innovative approach to study SS, performance, and the SE could be performed by comparing surgeons with different level of experience while performing natural and artificial SS, with an in-depth characterization of these measures by means of explicit measures of SS, SE, and performance (e.g., questionnaires and interviews); together with physiological indices (galvanic skin response, skin temperature, pupillometry), which are largely employed to detect the degree of SE toward a tool, but also the level of workload, cognitive engagement and stress level during task.

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Declaration of competing interest

The authors 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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Appendix A. Supplementary data

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