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Expert laparoscopist performance on virtual reality simulation tasks with and without haptic features

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Abstract

Background Virtual reality (VR) simulation for laparoscopic training is available with and without haptic feedback features. Currently, there is limited data on haptic feedback's effect on skill development. Our objective is to compare expert laparoscopists' skills characteristics using VR delivered laparoscopic tasks via haptic and nonhaptic laparoscopic surgical interfaces.

Methods Five expert laparoscopists performed seven skills tasks on two laparoscopic simulators, one with and one without haptic features. Tasks consisted of 2-handed instrument navigation, retraction and exposure, cutting, electrosurgery, and complicated object positioning. Laparoscopists alternated platforms at default difficulty settings. Metrics included time, economy of movement, completed task elements, and errors. Progressive change in performance for the final three iterations were determined by repeated measures ANOVA. Iteration quartile means were determined and compared using paired t-tests.

Results No change in performance was noted in the last three iterations for any metric. There were no significant differences between platforms on the final two quartiles for most metrics except avoidance of over-stretch error for retraction; and cutting task was significantly better with haptics on all iteration quartiles ($p < 0.03$). Economy of movement was significantly better with haptics for both hands for clip application ($p < 0.01$) and better for right hand on complex object positioning ($p < 0.05$). Accuracy was better with haptics for retraction and cutting ($p < 0.05$) and clip application ($p < 0.05$).

Conclusion Results showed higher performance in accuracy, efficient instrument motion, and avoidance of excessive traction force on selected tasks performed on VR simulator with haptic feedback compared to those performed without haptics feedback. Laparoscopic surgeons interpreted machine-generated haptic cues appropriately and resulted in better performance with VR task requirements. However, our results do not demonstrate an advantage in skills acquisition, which requires additional study.

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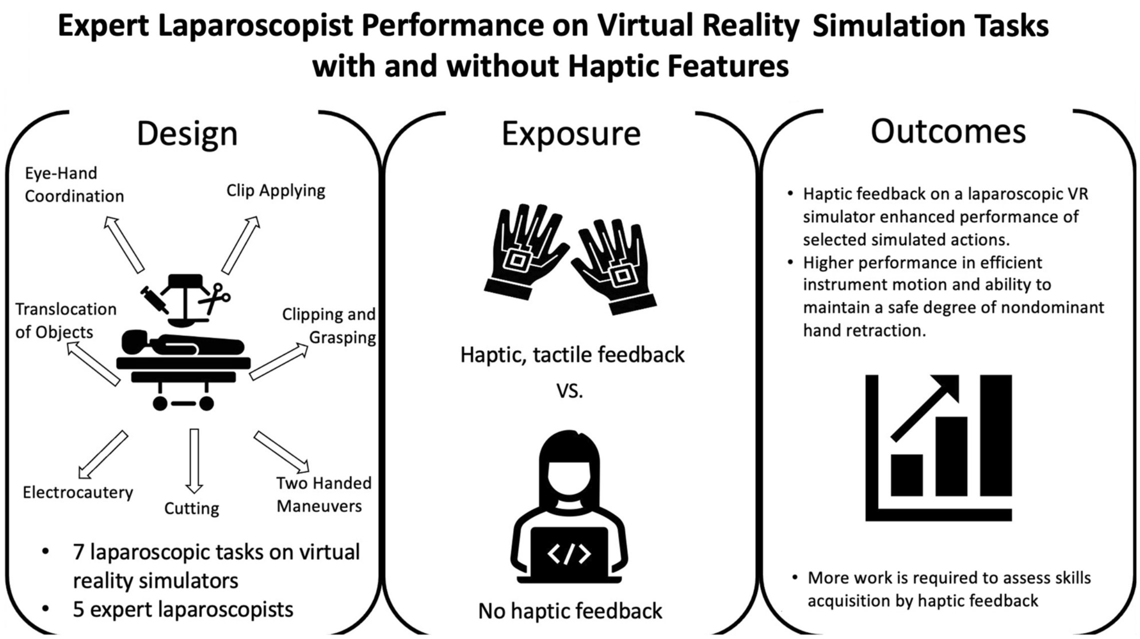
Graphical abstract



Keywords Virtual reality · Haptic feedback · Surgical simulation

The use of virtual reality (VR) surgical simulators to train laparoscopic skills was first described by Satava in 1993 [1] and VR platforms of various makes have been commercially available for more than 20 years. Simulation fidelity to real experience is linked not only to graphical renderings and object interactions, but also to the technical challenge of accurately rendering haptic cues, or a "sense of touch" to the user interface experience. This requires a complex mechanical force feedback apparatus and advanced computing to render a convincing and lag-free tactile experience which adds substantially to system cost [2]. Training with nonhaptic and haptic VR simulation devices has been shown to be effective in imparting laparoscopic skills although many publications which examine training effect on clinical laparoscopy have employed nonhaptic simulators [3]. Direct comparisons of skills characteristics of users of haptic and nonhaptic laparoscopic skills training platforms are few. Some historical "haptic vs. nonhaptic" studies have used VR devices with limited computing power or made use of nonstandardized tasks and non-VR videoscopic trainers for the "haptic" arm of prospective comparisons. Most studies have examined novice users. Results of such comparisons have been variable with claims of both more rapid and effective learning and lack of valuable training effect [4–6]. Despite past efforts, it is not truly known whether exclusion or inclusion of haptics delivery in a VR laparoscopic simulator impacts simulated laparoscopic performance. To better understand this, we characterized patterns of performance for expert laparoscopists, as opposed to new learners, using simulated laparoscopic tasks common to both haptic and nonhaptic versions of a VR simulation platform of recent manufacture. It was with the expectations that learning effect would be abbreviated and that any detected performance differences could be accounted for by presence or absence of haptics.

Materials and methods

This prospective cohort study was approved by the University of Massachusetts Chan Medical School – Baystate Health institutional review board [Project ID1793716-2] and all study activities were conducted in the Baystate Simulation Center – Goldberg Surgical Skills Lab.

Study design

Five expert laparoscopists (minimally invasive surgery fellowship trained and/or > 500 advanced laparoscopic cases in practice) volunteered to participate in this study. The study called for repetitive iterations of seven tasks (Fig. 1) on two Simbionix/Surgical Science VR laparoscopic simulators (Göteborg, Sweden), one with (LAP Mentor III) and one without (LAP Mentor Express) haptic feedback features. These tasks were selected from the preconfigured Simbionix

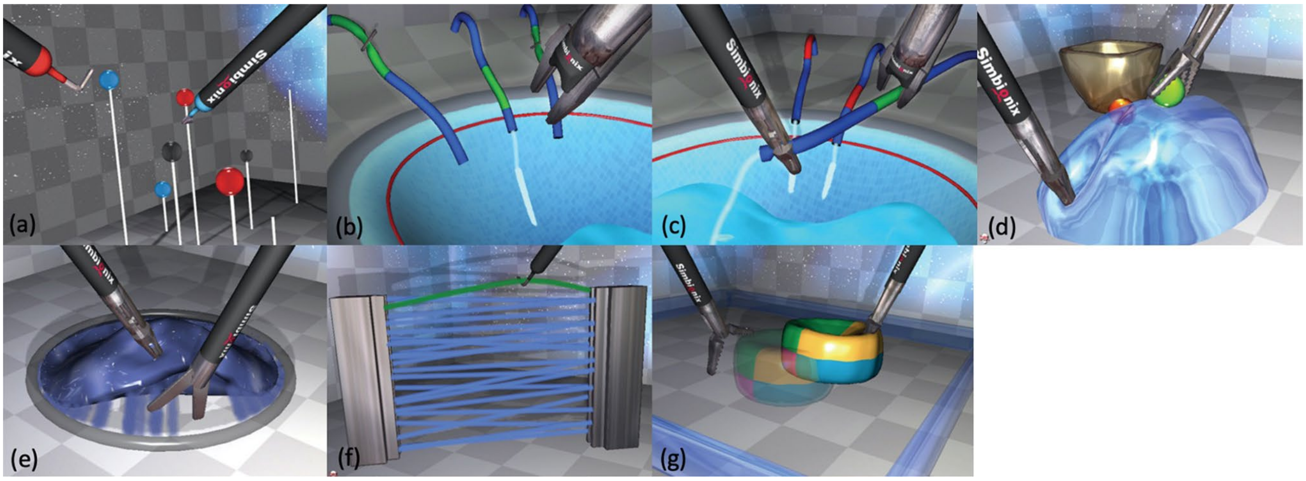


Fig. 1 The seven task modules completed by study expert laparoscopists. **a** Module 1: eye-hand coordination, **b** Module 2: clip applying, **c** Module 3: clipping and grasping, **d** Module 4: two handed maneuvers, **e** Module 5: cutting, **f** Module 6: electrosurgery, and **g** Module 7: Translocation of objects

9-task basic skills package based on the instrument-object interactions that would be expected to produce tactile sensations, and the need to use both right and left hands to complete the tasks. For this reason, laparoscope navigation tasks were excluded. For the purposes of the present report, the studied tasks are referred to as Modules 1 through 7. Graphical appearance of objects to be manipulated, instrumentation, task objectives and task metrics were identical on the two platforms, as shown in Table 1. However, user interfaces differed due to the force feedback apparatus in the LAP Mentor III system vs. the simple gimbaled instrument interface of the LAP Mentor Express (Fig. 2). Tasks incorporated 2-handed instrument navigation, retraction and exposure, cutting, electrosurgery, and complicated object positioning. All participants would alternate platforms at default difficulty settings for at least 12 iterations on each, and performance measurements were captured to the Simbionix cloud storage system for subsequent retrieval and analysis.

Statistical analysis

Trends for the final three iterations of each task for each task metric was analyzed using repeated measures ANOVA (Graphpad Prism, Graphpad Software, LLC). All sequential iteration results for each metric were grouped into four averaged quartiles. Iteration quartile means and standard deviations were determined for each measure, and the difference between haptic vs. nonhaptic performance was assessed using paired t-tests. Statistical significance was set at $p < 0.05$.

Table 1 Specific machine measurement types for each of the modules that were completed by study participants

Module 1 Eye-hand coordination	Module 2 Clip applying	Module 3 Clipping and grasping	Module 4 Two handed maneuvers	Module 5 cutting	Module 6 Electrocautery	Module 7 Translocation of objects
Time to completion (s)	Time to completion (s)	Time to completion (s)	Time to completion (s)	Time to completion (s)	Time to completion (s)	Time to completion (s)
Right hand economy of movement (%)	Right hand economy of movement (%)	Right hand economy of movement (%)	Right hand economy of movement (%)	Safe retraction rate (%)	Efficiency of cautery (%)	Total path length of right instrument (cm)
Left hand economy of movement (%)	Left hand economy of movement (%)	Left hand economy of movement (%)	Left hand economy of movement (%)	Accuracy rate of cutting without injury (%)	Accuracy rate of cutting bands (%)	Total path length of left instrument (cm)
Accuracy of touch target (%)	Accuracy of applied clips (%)	Accuracy of applied clips (%)	Number of balls collected		Number of bands not cut	Efficiency of object translocation (%)
Number of touched balls	Number of clipped ducts	Number of clipped ducts	Number of balls lost			Number of correctly placed objects

Fig. 2 Surgical interface for the haptic (right panel) LAP Mentor III and nonhaptic (left panel) LAP Mentor Express simulators. The added bulk of the haptic platform's interface is required to accommodate the electromechanical force feedback apparatus that drives the haptic cues experienced by the user holding the instrument handles

Results

Three male and two female surgeons participated. All were members of the General Surgery Division at Baystate Health and all were actively engaged in practice that included advanced laparoscopic surgery (foregut, enterocolonic, bariatric, solid organ). All surgeons had prior experience with laparoscopic simulators but none had prior practice experience using Simbionix systems, which were newly acquired in 2021 in our simulation lab. All were right-handed.

All surgeon participants completed 12 iterations of every modules on each simulator. Comparison of averages of the last quartile for haptic and nonhaptic task performance did not reveal significant differences for Modules 1, 3, 4 or 6 for any of the study metrics. For these modules, no significant changes occurred over the final three iterations to suggest a significant ongoing learning effect. Differences between haptic and nonhaptic platforms were observed for final quartile performance for Modules 2, 5 and 7 for selected metrics, however. The majority of differences favored performance on the haptic platform and are shown in Fig. 3, contrasting with selected metric results that did not show

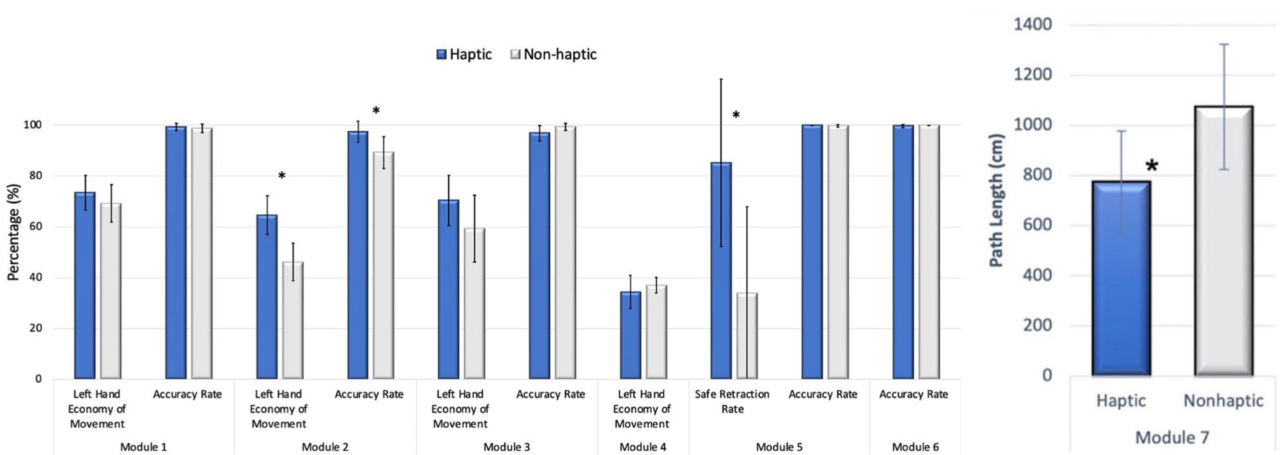


Fig. 3 Comparison of performance on VR simulators with and without haptic feedback on the seven modules for the last quartile iterations (iterations 10–12) shown for selected measurements. An asterisk signifies significant difference between haptic and nonhaptic. During the final iterations, when no significant change was observed for successive performance results for each measure, performance on the haptic platform was higher than that observed for the nonhaptic platform for Modules 2, 5 and 7 for left hand economy of motion and accuracy of clip application (Module 2), safe retraction (Module 5), and left instrument path length (Module 7). Time to task completion, the results of which did not show significant differences for any of the comparisons, are not shown

these differences. Findings include higher performance on the haptic platform for: (1) left hand economy of motion and accuracy of clip placement (Module 2—*clip applying*); (2) safe retraction (Module 5—*cutting*); and (3) left instrument path length (Module 7—*translocation of objects*). Time to task completion and right hand economy and path length did not differ between haptic and nonhaptic platforms for any of the comparisons of final quartile results.

The most notable differences were for Module 2 and Module 5, where better performance on haptic platform was observed for the last three quartiles for economy of motion on Module 2 (43% vs. 40.1%, $p=0.01$ second quartile; 57.6% vs. 37.8%, $p<0.01$ third quartile, and 64.6% vs. 46.1%, $p<0.01$ fourth quartile), and all four quartiles for safe retraction on Module 5 (67.5% vs. 26.3%, $p=0.02$ first quartile; 85.6% vs. 23.4%, $p<0.01$ second quartile; 96.3% vs. 33.5%, $p<0.01$ third quartile; 85.2% vs. 33.9%, $p=0.02$ fourth quartile) (Fig. 4). Other differences for selected metrics between haptic and nonhaptic platform performance were either isolated or were for quartile results earlier in task performance than the final quartile. In Module 2- *Clip Applying*, economy of movement for right hand was significantly better for the haptic than the nonhaptic platform for the first three quartiles (66.9% vs. 52.2%, $p=0.03$ first quartile; 74.1% vs. 56.0%, $p<0.01$ second quartile, and 78.3% vs. 60.6%, $p<0.01$ third quartile). This difference was lost for the final quartile in contrast to left hand economy of motion, which was significantly better for the haptic platform for the last 3 quartiles, as noted above. (Fig. 4). Again, for Module 2, in addition to higher clip application accuracy for the final quartile (97.4% vs. 89.2%, $p=0.02$), accuracy for the haptic platform was higher for the second quartile as well (92.9% vs. 87.8%, $p=0.05$). In Module 3, *Clipping and Grasping*, right hand economy of motion performance was better for haptic than nonhaptic platforms for the first quartile (70.6% vs. 56.6% for, respectively, $p=0.01$).

For Module 7, *Translocation of Objects*, left hand path length was significantly shorter for the haptic platform than nonhaptic (774 cm vs. 1074 cm, $p=0.03$) for the final quartile. Despite the left hand path length advantage for the haptic platform, efficiency of translocation was higher for the first (72.9% vs. 93.7%, $p<0.01$) and third quartiles (86.1% vs. 96.3%, $p=0.04$) for the nonhaptic platform performance compared to haptic. This was the only measure for any module for which an advantage was observed for the nonhaptic platform. No such difference was observed for the fourth quartile, however.

Discussion

The acquisition of laparoscopic skills can be achieved through multiple avenues of lab-based practice. The available options beg the question: "how can skills development be optimized?" Although VR training cannot be described as the predominant method, its use is quite common and training centers have several options pertaining to VR when considering procurement of laparoscopic simulation devices. Irrespective of the specific manufacturer of a simulator, the choice of haptic and nonhaptic platforms has implications for cost and potential implications for fidelity to clinical laparoscopic surgery.

Published studies specifically examining the value of haptic feedback in VR laparoscopic simulators have tended to focus on rate of development of skills in VR and not on the question of whether the presence or absence of haptics fundamentally affects laparoscopic performance. From the standpoint of performance impact of haptics, results have

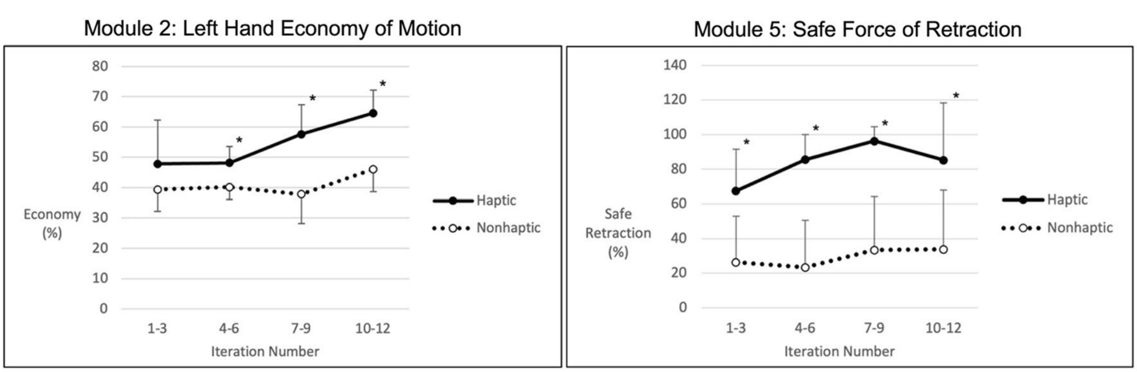


Fig. 4 Comparison of performance for successive iteration quartiles for haptic (solid symbols) vs. nonhaptic (open symbols, dotted line) for Modules 2 and 5 measures metrics impacted most by haptic characteristics. Module 2 requires accurate positioning of a clip applier instrument on a tubular structure followed by application of a clip, alternating left and right hand roles. Module 5 requires nondominant hand retraction of an object in order to reveal cord-like structures that are cut with a laparoscopic endoshear. With excessive retraction force, the retracted object slips from the grasping instrument and must be regrasped. Results of both exercises suggest that the presence of haptic cues allowed surgeons to make positioning adjustments more efficiently in Module 2 and to maintain appropriate retraction force more effectively for Module 5, with statistically significant differences for the quartiles marked with asterisks

been mixed. Experimental models have varied significantly, and the majority of studies has actually compared VR performance as the nonhaptic study arm vs. a videoscopic or augmented reality videoscopic trainer [6–9]. Among the problems associated with such an approach is the necessity to base comparisons of haptic and nonhaptic platforms on different tasks performed on radically different systems. Direct comparisons of haptic and nonhaptic VR platforms have focused on novice users (e.g. medical students) [5, 6, 10] or, in the case of Våpenstad et al. [11], focused less on surgeon performance than on perception of the realism of the haptic experience, which was not generally well perceived based on post-use surveys.

We felt that the question would best be addressed by presenting expert laparoscopists with identical laparoscopic tasks on a common simulator software platform but performed with both haptic and completely nonhaptic VR interfaces. We assumed that some early learning effect would likely be observed but that, in contrast to variable learning rates that might be observed for novice laparoscopists, learning curves would flatten promptly for study metrics and any differences between haptic and nonhaptic performance would be due to the fidelity implications of the haptic experience. In this study, most such differences were small and observed for selected metrics. There was one exception, however. The cutting task (Module 4) requires elevation of a graspable object which reveals cord-like attachments to a deeper surface. This retraction has limits on the force that can be applied before the object is pulled out of the grasping instrument. The degree of "pull" that is allowed becomes rapidly evident as the user performs the task. Very consistently, across all iteration quartiles, retraction performance was higher with haptics when resistance to "pull" forces could be felt through the retracting instrument. Although a visible cue was also available to help define over-retraction, expert surgeons responded better when a sense of resistance to retraction force was present. Taken with the results favoring performance on the VR platform for motion characteristics across four of the seven modules, the inclusion of haptics appears to aid improved surgeon performance in simulated laparoscopy.

Among the factors that may contribute to a positive modern study outcome for haptics use is the computing hardware installed in each simulator. Ours is one of the handful of studies to assess the effect of haptics on user performance in VR laparoscopy in the past 10 years. Over the period of time that laparoscopic VR simulation has been available, tremendous advances in computer hardware and software technology have improved graphical fidelity and lag time characteristics of simulator haptics [12, 13]. Lag in delivery of haptic cues, which on average was two seconds a decade ago, has essentially been eliminated [14, 15]. Corresponding to this, a 2019 systematic review of 87 pertinent articles suggests a positive trend in training effects for complex tasks with the addition of haptics to VR simulators [13].

The strengths of the present study are (1) the homogeneous participant group for whom differences in haptic/nonhaptic performance can be attributed to the haptic characteristics of the platforms used; (2) matched comparisons of performance with haptic/nonhaptic interfaces for individual surgeon participants; and (3) the use of common task software, only varying the user interface. Although the force feedback can be defeated on the LAP Mentor III, we felt it was important to make the comparison to a simulator without the force feedback apparatus to help inform the value proposition for two platforms with a large difference in procurement costs. Although we feel our study design permitted very directed analysis of the effects of haptics on laparoscopic performance in VR, we cannot claim that current haptic fidelity makes a VR simulator experience equivalent to that experienced with videoscopic box trainers which have served as the basis for many past comparisons with nonhaptic VR systems. In addition to this, limitations of our work include the relatively small number of study participants and the single cohort study design. By alternating use of the two platforms, some task learning on one platform may aid in performance on the other. A randomized prospective study design would prevent any confounding effect of exposure to both platforms, although matched comparisons of performance would not be feasible. We opted to conclude successive iterations at 24 (12 on each platform). This does not signify that some incremental improvement could not occur or that the significant differences in performance between the haptic and nonhaptic platforms would not eventually be abolished with additional iterations.

Conclusion

Haptic feedback on a laparoscopic VR simulator platform used for this study enhanced performance of selected simulated actions, most notably efficient instrument motion characteristics and the ability to maintain a safe degree of nondominant hand retraction while a dominant hand cutting task was performed. This supports the concept that laparoscopic haptic features can provide a degree of meaningful realism for the user that is not experienced without these haptic features. However, this does not necessarily speak to the effects of haptic feedback on skills acquisition for more typical learner groups or downstream benefits to clinical performance. Despite the use of haptic VR simulators for two decades, these aspects of simulation fidelity require ongoing investigation.

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Declarations

Disclosures Dr. Margaret Siu, Dr. Kaitlin Debbink, Amanda Duda, Dr. George Orthopoulos, Dr. John Romanelli, Dr. Jacqueline Wu, and Dr. Neal E. Seymour have no conflicts of interest or financial ties to disclosure. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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