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I feel a moving crowd surrounds me: Exploring tactile feedback during immersive walking in a virtual crowd

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Abstract

The aim of our study was to investigate whether different tactile feedback conditions could affect the behavior of participants who were instructed to walk within a virtual reality environment surrounded by a virtual crowd of people. A road crossing scenario that takes place in a virtual metropolitan city was developed for this study. Participants were asked to walk toward the opposite sidewalk while wearing a tactile vest. At each road crossing, one of several tactile feedback conditions was generated, including No Tactile, Side Tactile, Back Tactile, Front Tactile, Accurate Tactile, and Random Tactile. During the virtual road crossing, the movement of the participants was captured, and movement-related measurements were extracted and analyzed to evaluate the effects of tactile feedback on the participant's movement behavior. Additional data were collected through the distribution of a questionnaire to consider self-reported ratings of the experimental conditions. The results revealed that tactile feedback conditions had significant effects on movement behavior, while the participants' ratings also indicated that they were affected by the tactile feedback conditions. We found that when the participants were immersed in a high-density crowd simulation, they became sensitive to tactile feedback. However, they were not able to distinguish between the accurate feedback and the random feedback.

KEYWORDS

human–crowd interaction, human movement, self-reported ratings, tactile feedback, virtual crowd

1 | INTRODUCTION

With the recent growth in the use of virtual reality devices and interfaces, people can experience and immerse themselves in virtual environments that are completely different from the place they are actually located. In addition to the visual information provided to virtual reality (VR) users, which is sent through the head-mounted display that is used to project the virtual content so they have a compelling VR experience, the aural, haptic, proprioceptive, and vestibular systems should also be engaged during the experience.[1,2] However, achieving a compelling experience is not easy because several additional pieces of equipment are necessary.

Considering the recent advances in commercial VR tactile feedback devices that have been developed to give users the ability to sense a VR experience, a study on human body contact imposed through a wearable tactile vest was conducted. This study combines the tactile feedback with the ability of the VR headset to track the user's position and visually place the users within a virtual environment, where they were asked to perform a walking task surrounded by a virtual crowd

FIGURE 1 A participant surrounded by and observing a virtual crowd of people while walking at the motion capture studio, and consequently crossing the virtual crosswalk

of people. Although it is known that tactile feedback can be used to guide users and help with navigation,[3-6] and there are numerous studies that have also explored the impact of tactile feedback on participants' self-reported ratings,[7-10] there is limited research that has investigated the impact of tactile feedback on participant movement and self-reported ratings, and more specifically, on whether and how tactile feedback affect participants surrounded by a virtual crowd.

Due to these limitations, understanding how tactile feedback may or may not affect movement behavior and self-reported ratings of users could be very beneficial for virtual reality developers because it would allow them to develop certain aspects of VR experiences, including the effective use of tactile feedback and immersive interaction with virtual crowds. Thus, this study further explored the impact of tactile feedback when participants were immersed in a virtual reality scenario and asked to walk while being surrounded by a moving virtual crowd of people. Consequently, a simple scenario was developed that placed participants at a road crossing (i.e., crosswalk) in a virtual metropolitan city surrounded by a virtual population. While wearing a tactile vest, participants were asked to walk across the virtual crosswalk (see Figure 1) until they reached the opposite sidewalk while one of the six tactile feedback conditions (i.e., No Tactile, Side Tactile, Back Tactile, Front Tactile, Accurate Tactile, and Random Tactile) was applied and examined. We chose to immerse the participants in a virtual crowd to provide a VR experience that allowed for tactile feedback to be considered in combination with the visually projected content because other studies[11,12] have demonstrated that tactile devices can trigger sensations when the stimulus is associated with the virtual environment and the task.[13]

During the road-crossing task that participants were instructed to perform, the trajectory of each participant was captured, and measurements related to the movement behavior of the participants were obtained. Additionally, immediately after the end of each condition, participants were asked to complete a questionnaire concerning their experience with the tactile feedback. The aim of this study was to answer the following research questions based on the collected data:

- *RQ1:* Did the tactile feedback affect the movement behavior of participants across the experimental conditions?
- *RQ2:* Were there differences in participants' self-reported ratings across the experimental conditions?

2 | RELATED WORK

The following two subsections present work related to interaction with virtual crowds and tactile feedback in virtual environments.

2.1 | Interaction with a virtual crowd

Apart from studies concerning single character interaction,[14,15] several studies have been conducted to explore interactions in small groups of virtual characters and virtual crowds.[7,16-19] To further investigate how users regulate or coordinate their movement behaviors during interactions with virtual characters, previous studies have explored follower behavior,[20,21] side-by-side[22] and face-to-face walking,[23] group formations,[24] and collision avoidance tasks.[25,26]

These previous studies yielded a number of interesting results that are applicable in several different VR domains. First, it was found that interactions in which virtual characters violated the personal space of humans resulted in negative reactions by the participants.[27,28] As a result, participants walking along with virtual characters tended to maintain a safe distance, especially when the virtual character was considered to be realistic.[29] In a similar context, it was revealed that humans tended to keep more distance when moving toward virtual characters from the front than they did when moving toward virtual characters from behind.[30] Another study conducted by Bruneau et al.[31] investigated the relative motion and visual aspects of a virtual crowd. In their study, the motion of a user-controlled character was captured, although, it is important to note that participants were asked to use a joystick to control their virtual character instead of performing the physical act of walking. The results of this study revealed that humans followed longer paths when surrounded by a high-density virtual crowd.

Other studies have investigated the movement coordination of participants. Such studies included real[32-34] and virtual reality[1,35,36] scenarios with people coordinating their movements while crossing an intersection in the presence of either a human or a virtual character. A series of studies[37-39] found that two humans tended to become more sensitive to the each other's presence. They also tended to simultaneously change their decisions or actions when they crossed the road as part of a group, compared with when they crossed a road alone. In a human–virtual crowd interaction study, Warren[40] found that participants (followers) tended to match the crowd leader's velocity rather than keep a constant distance from the leader. Rio et al.[41] investigated interactions within a crowd in a neighborhood to determine which neighbors influenced pedestrian behavior, the influence of the neighbor's position, and the influence of combining multiple neighbors. They found that neighbor influence is linearly combined, while it decreased with distance but not with lateral position. Finally, Nelson et al.[42,43] individually investigated density, speed, and direction variations of a virtual crowd and found that the speed of the virtual crowd affected human movement. They found that both the density and the speed of a crowd affected the movement behavior of the participants.

2.2 | Tactile feedback

The most common way to deliver tactile feedback is by using vibrotactile feedback devices. Such devices have been extensively used,[44,45] and the tactile feedback provided through these devices have successfully enhanced the sense of realism of interactions within a virtual environment.[8-10,46] Previous studies indicated that tactile feedback can improve users' performance within the virtual environments,[13,47] as participants have reported that the virtual environment they interact with becomes more realistic when tactile feedback is included in the experience.[48] According to Lee et al.,[13] this occurs because more senses are engaged during the virtual reality experience, though such findings have been restricted to cases where the additional stimuli are associated with the virtual environment and the given task.

In this study, a tactile vest was used to induce the contact sensation during close interactions with virtual characters. Tactile vests have been used in various domains, including human–virtual character interactions,[7] training,[49] medicine,[50] rehabilitation,[51] and serious games.[52,53] In this case, we investigated how a participant's movement behavior was affected as they walked within a virtual crowd of people, with tactile feedback being generated every time a virtual character collided with the invisible presence of the participant.

To understand how participants perceived the provided tactile feedback, most studies have explored the variations in captured human responses.[7] It has been suggested that haptic feedback patterns can be used to transmit valuable information to users.[54] Moreover, a tactile pattern that describes the interaction appropriately has been shown to improve the realism of that interaction,[46] which was especially true when users received logical tactile feedback versus illogical feedback or tactile feedback that was perceived as inaccurate.[7] The user's sense of presence[55,56] and embodiment[57] has also been shown to increase when haptic feedback is provided, while it also affected the participant's emotional state (valence, arousal, and dominance).[58] However, prior studies have not definitively determined whether and how tactile feedback affects the movement behavior and self-reported ratings of participants during their immersion in a virtual crowd of people.

Since tactile feedback is associated with the virtual environment and task,[13] understanding how different tactile feedback conditions affect humans could be used to further improve both the realism of such interactions and the overall VR experience. Several studies[3-5] have been conducted on how tactile feedback can guide a user. Other studies have also demonstrated how different tactile feedback conditions affect the self-reported ratings or participants.[6,59,60] However, to the best of our knowledge, there has been little or no research that examines the effects of tactile feedback on human movement behavior while the user walks as they are surrounded by a virtual crowd of people. Thus, the main contribution of this research is the investigation of how the movement behavior is affected by tactile feedback patterns.

3 | METHODS

3.1 | Participants

An a priori power analysis was conducted to determine the appropriate sample size for this study using G*Power version 3.1.9.3 software.[61] The calculation was based on 95% power, a medium-effect size of 0.25,[62] six conditions, a nonsphericity correction $\epsilon = 0.60$, and an $\alpha = .05$. The analysis resulted in a recommended sample size of 42 participants. Of the 42 recruited students from our university, nine were female and 33 were male, ranging in age from 19 to 27 years ($M = 21.55$, $SD = 2.33$). None of the participants reported nausea or cybersickness, and no students reported motor implications or musculoskeletal disorders that might have affected their movement behavior.

3.2 | Lab space and equipment

This experimental study took place at the departmental motion capture studio, which is 8-m long and 8-m wide, with a ceiling height of 4 m. Other than a desk and two desk chairs positioned along the sidewall of the studio, the remainder of the environment was free from obstructions, so participants were able to walk freely during the experiment. The equipment used to present the developed experimental conditions to the participants included an HTC Vive Pro to project the virtual reality content and a bHaptics tactile vest to provide tactile feedback. In addition, the MSI VR One backpack computer was used to run the experimental application. A participant wearing all gear used for this study is shown in Figure 2.

3.3 | Virtual reality application

The Unity3D game engine was used to develop the application, and Autodesk 3ds Max was used to design the virtual environment (i.e., the metropolitan city) that was used to immerse participants. The virtual characters that belong to the virtual crowd were designed in Adobe Fuse and rigged in Adobe Mixamo. The animations assigned to virtual characters

FIGURE 2 A participant wearing all devices (HTC Vive head-mounted display, bHaptics tactile vest, and MSI VR One backpack computer) used for this study

were downloaded from the Unity Asset Store, and the characters were animated using the Mecanim animation engine of Unity3D. Path planning of virtual characters was performed using the NavMesh functionality of Unity3D.

The virtual characters were constantly generated once per second from 10 spawn points placed behind the participant's position in the virtual environment. Each character's crossing was repeated multiple times. The virtual pedestrians (i.e., the virtual crowd) were scripted to cross the virtual crosswalk and reach target positions on the opposite sidewalk. The virtual crowd followed a forward direction when crossing the virtual crosswalk. However, after each character reaching the opposite sidewalk, each one was assigned to either move to the right or the left on the virtual pavement to alleviate congestion. Figure 3 illustrates the virtual environment and a generated crowd simulation used for this experiment from a bird's-eye perspective.

The simulated crowd was designed with a high density (2.5 characters per square meter, see Figure 4), as proposed by Still,[63] since we wanted the virtual characters in the virtual crowd to violate the intimate space of the participants. Specifically, we wanted to provide tactile feedback associated with the visual information that participants received via the VR headset. The objective was to ensure participants considered the tactile feedback as realistic to provide the illusion that it was associated with their collisions with the virtual characters. This is also supported by a prior study conducted by Lee et al.[13] that showed tactile feedback combined with visual information enhances the perceived realism of interactions.

The virtual reality scenario was set to take place during the daytime, and therefore, sunlight was used to light the scene. To create a virtual reality experience that matched the real-life scenario, sound effects related to a metropolitan city full of pedestrians were also added because prior studies indicated that sound related to the visual content enhances the sense of presence of participants in a virtual environment.[64] Another important aspect of the virtual environment is related to the

FIGURE 3 From a bird's-eye view, the metropolitan city and the virtual crowd that was used to immerse participants in this experimental scenario

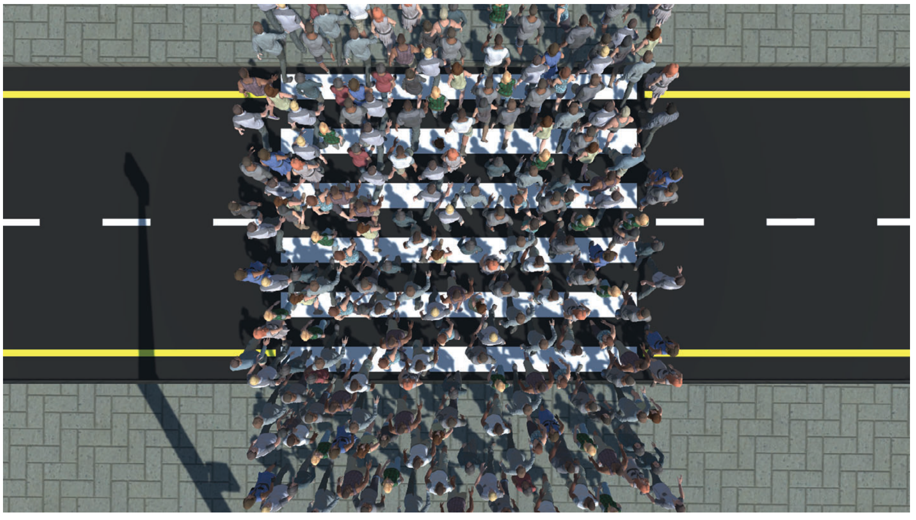

FIGURE 4 The high-density crowd model (2.5 characters per square meter) that was used in the experimental study

participants' self-presence within it. Specifically, a self-avatar was not incorporated to represent the participants for two reasons. First, a prior study indicated that a self-avatar may alter the movement behavior of the participants[25] within a virtual environment because participants can become more sensitive to their virtual body. Secondly, to effectively represent participants, a motion capture system should be used. During our pretesting period, people reported feeling uncomfortable wearing an inertial motion capture system device with the rest of the equipment used for this study. Therefore, such a device was not included. Finally, it is important to note that the distance between the two sidewalks in the virtual environment was seven meters.

3.4 | Experimental conditions

A total of six experimental conditions were developed to understand the effects of tactile feedback on human movement behavior and changes in the self-reported ratings during immersive human–crowd interaction. It should be noted that each condition was performed by each participant only once, as in Mousas et al.[25] The six experimental conditions included the following:

- *No Tactile Feedback (NT):* In this condition, no tactile feedback was provided to the participants during the walking task. However, the participants were still asked to wear the tactile vest. This condition was included in our experimentation to establish a baseline condition in which participants walk without being influenced by any form of tactile feedback. This condition could be used to better understand the movement behavior of participants based only on visual information, while it could also help to identify and understand any differences in the participants' movement behavior between the no tactile condition and the tactile feedback conditions.
- *Side Tactile Feedback (ST):* This condition was used for tactile feedback that was generated on the left side or right side of the tactile vest. This condition was included to better understand whether and how contacts that occur on only one side would impact the participants walking motion. Before beginning the walking task, either the right or left side tactile actuators were chosen randomly, and the chosen side actuators were activated every time there was a collision with a virtual character on that side of the invisible presence of the participant. The actuators remained active for the duration of the collision.
- *Back Tactile Feedback (BT):* For the BT condition, only the actuators located on the backside of the tactile vest were used and were activated every time there was a collision with a virtual character walking behind the participant. The back actuators also remained active for the duration of the collision.
- *Front Tactile Feedback (FT):* Similar to the BT condition, the FT condition included the activation of the actuators located on the front part of the tactile vest every time a participant collided with a virtual character walking in front of the participants. The front actuators also remained active for the duration of the collision.
- *Accurate Tactile Feedback (AT):* For this condition, all actuators were used to provide sensory stimuli for collisions with the virtual characters. For the AT condition, the participants received tactile feedback every time a collision (contact) between a body part of the invisible self-avatar and virtual characters occurred. Once a collision between the body parts (colliders) was detected, the actuator on the tactile vest that was assigned to the specific body part was also activated for the duration of the collision.
- *Random Tactile Feedback (RT):* For the RT condition, randomly generated tactile feedback was received by the participants. To develop the RT feedback condition, during the preprocessing stage, we randomly assigned a random sequence and timestep to each actuator (tactor) that would be activated, and each actuator was set to remain active and provide tactile feedback to the participants for one second. The random initialization was performed only once, and the output configurations for each actuator were stored so all participants experienced the same random tactile feedback condition.

3.5 | Measurements

To determine how participants perceived and reacted across the six different tactile feedback conditions, both objective (i.e., movement behavior) and subjective (i.e., self-reported ratings) data were collected, which are described below in the following subsections.

3.5.1 | Movement measurements

Our participants' movement behavior was captured using the position tracking functionality of the HTC Vive head-mounted display and a wireless Xsens inertial measurement unit (IMU) sensor attached to the participant's chest. The tracking functionality of the HTC Vive was used to capture the first five measurements presented below, and the IMU sensor was used to capture the sixth measurement (i.e., direction) of the participants. Thereafter, the collected data were downsampled in 100 equidistant points. The six measurements that represented the spatiotemporal properties of human movement included the following:

- *Speed:* The average speed of the participant's walking motion when crossing the virtual crosswalk. The speed was measured in meters per second.
- *Length:* The total trajectory length (traveled distance) of the participant. The length of the captured trajectory was measured in meters.
- *Duration:* The time needed for the participant to cross the virtual crosswalk (reach the opposite sidewalk). The duration was measured in seconds.
- *Smoothness:* The smoothness was computed as the average jitter of the trajectory.[65] Low jitter values denoted a smoother trajectory. The smoothness was measured in meters.
- *Deviation:* The average deviation (absolute value) of the participant upon reaching the opposite sidewalk. The deviation was computed using the difference between the participant's initial x-axis position (i.e., the initial position at the sidewalk) and final x-axis position (i.e., the final position at the opposite sidewalk). The deviation was measured in meters.
- *Direction:* : The average absolute y-axis rotation on the (x,z) plane of the participant when walking toward the opposite sidewalk. The direction was measured in degrees. Zero degrees indicated that the participant was moving parallel to the segment that connected his/her initial position and the forward position on the opposite sidewalk.

3.5.2 | Subjective measurements

A questionnaire was developed to collect subjective ratings (i.e., questionnaire responses) to investigate the effects of tactile feedback conditions in the participants' experiences during their exposure to the six experimental conditions. The developed questionnaire (see supplementary material) included 12 items. Q1 and Q2 were designed to investigate the realism of tactile feedback. These questions were adapted from Wilson et al.[66] Q3 and Q4 were designed to investigate the emotional reactivity to the tactile feedback, and Q5 and Q6 investigated the emotional reactivity associated with crowd interaction. Q3–Q6 were inspired by methods in Mousas et al.[15] Q7 and Q8 explored the participants' sensation of colliding with the virtual bodies and was developed by the authors of this article. Q9 and Q10 explored body ownership and were adopted from Slater et al.[67] Finally, Q11 and Q12 evaluated participants' presence and were adapted from Slater et al.[68] It should be noted that some questions were adjusted to fit the purpose of this experiment. Moreover, participants who were exposed to the no tactile (NT) feedback condition were not asked questions regarding tactile feedback (Q1–Q4). The questionnaire was distributed to participants in a paper-based format after they completed the movement segment of each tactile feedback condition. Finally, in addition to the questionnaire, the participants were also allowed to include comments or concerns about the study in a designated space provided on the questionnaire.

3.6 | Procedure

Once the participants arrived at the motion capture studio, the researchers provided information about the experimental procedure. Participants were given a consent form to read, which was approved by the Institutional Review Board of our university. They were then asked to sign it to indicate that they agreed to participate in the experimental study. A paper-based demographic questionnaire was then handed to the participants. The research team helped the participants put on the tactile vest, the IMU sensor, the backpack computer, and the head-mounted display. The research team asked participants to walk within a virtual replica of the motion capture studio for a few minutes to ensure that all participants were able to walk safely and were comfortable wearing all gear used for this study.

Before beginning the experiment, participants were told they would be placed in a virtual metropolitan city and surrounded by a virtual crowd of people. They were told that once the traffic light turns to green, the virtual crowd will start moving toward the opposite sidewalk. They were instructed that they should also cross the street in the virtual crosswalk to reach the opposite sidewalk. Participants were told that once they reached the opposite sidewalk, an on-screen instruction will tell them to stop moving, and a black screen will then appear. At that time, they were told to take off the head-mounted display and walk to the desk and complete the paper-based questionnaire. After completing the questionnaire, the participants were told they should go back to the marked location and prepare for the next condition. This process was repeated for each of the six conditions used in the experiment. The balance for first-order carry-over effects between the experimental conditions was ensured using Latin squares.[69] The participants were also informed that if they got close enough to the sidewalls or too close to the front wall of the motion capture studio, an on-screen message would warn them to stop walking to prevent risk of accidental injury. It should be noted that none of the participants collided with any of the walls during the study.

The participants were told that they could have additional breaks between each condition and had full permission to withdraw from the study at any time. They were also told that they would be informed when the experiment had ended. After the end of the study, the researchers helped the participants remove the head-mounted display, the backpack computer, the tactile vest, and the IMU sensor. The research team asked the participants if they were willing to answer questions about the study. At that time, participants were also asked to express their thoughts about the experiences and provide feedback regarding their movement behavior, tactile feedback, and interaction with the virtual crowd. None of the participants spent more than 45 min in the lab.

4 | RESULTS

The results of this study are presented in the two subsections below. We compared the movement behavior measurements and self-reported ratings from the participants across the experimental conditions to determine whether the tactile feedback conditions affected participants' movement and ratings. To analyze the collected data, a one-way repeated analysis of variance (ANOVA) was used. The experimental conditions were defined as independent variables and the movement measurements and self-reported ratings were used as the dependent variables. The post hoc differences were evaluated using Bonferroni corrected estimates when the ANOVA was significant. The normality assumption of the movement-related measurements and self-reported ratings were evaluated graphically using Q-Q plots of the residuals,[70] and the Q-Q plots indicated that the obtained data fulfilled the normality assumption. Moreover, the internal validity of the individual components of the questionnaire was measured using Cronbach's alpha coefficient, yielding scored $.72 < \alpha < .97$. With sufficient scores, we used a cumulative score for each of the two items that belong to each questionnaire component.

4.1 | Movement behavior

Each of the six movement measurements were statistically analyzed across the six different experimental conditions. Descriptive statistics are provided in supplementary material document and boxplots of the obtained data are presented in Figure 5. The statistical analysis did not show significant results for smoothness, $\Lambda = .756$, $F(5,37) = 2.395$, $p = .056$, $\eta_p^2 = .244$, or direction, $\Lambda = .903$, $F(5,37) = 1.820$, $p = .133$, $\eta_p^2 = .197$, measurements across the experimental conditions.

The statistical analysis revealed significant results for the speed measurement, $\Lambda = .422$, $F(5,37) = 10.141$, $p < .001$, $\eta_p^2 = .578$. Post hoc results showed that the mean speed of participants under the FT condition was significantly lower than that of the NT condition at the $p < .001$ level, the BT condition at the $p < .001$ level, and the AT condition at the $p < .05$ level. Moreover, the participants' mean speed of the RT condition was significantly lower than that of the NT condition at the $p < .05$ level and the BT condition at the $p < .001$ level.

Regarding the length measurement, the statistical analysis also provided significant results, $\Lambda = .286$, $F(5,37) = 18.485$, $p < .001$, $\eta_p^2 = .714$. Post hoc results showed that the mean lengths of the NT, BT, FT, and AT conditions were significantly lower than those of the ST and RT conditions, all at the $p < .001$ level.

The duration measurement was found to be significant across the experimental conditions, $\Lambda = .403$, $F(5,37) = 10.966$, $p < .001$, $\eta_p^2 = .597$. Post hoc results indicated that the mean duration of the BT condition was significantly lower than that of the ST condition at the $p < .05$ level, the FT condition at the $p < .001$ level, and the RT condition at the $p < .001$ level.

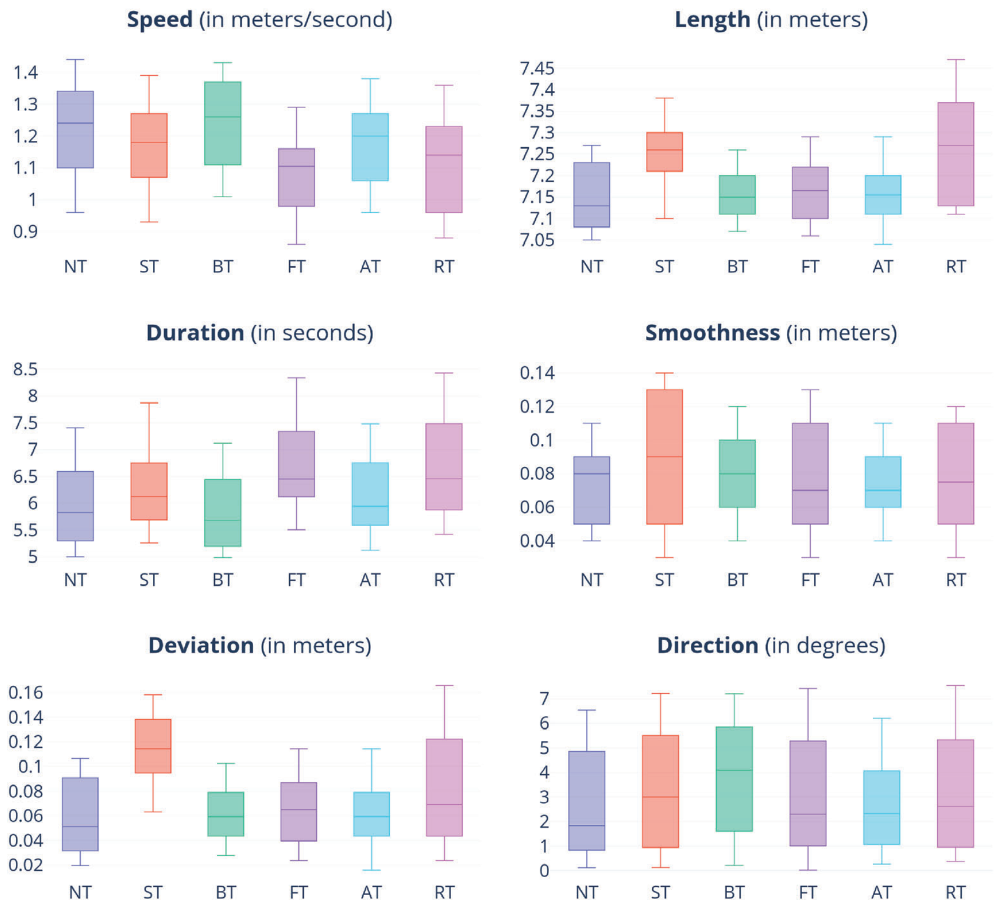

FIGURE 5 Boxplots of the movement measurements. Boxes enclose the middle 50% of the data. The median is denoted by the thick horizontal line. See the supplementary material document for means and standard deviations

Moreover, the mean duration of the FT condition was significantly higher than that of the NT condition at the $p < .001$ level, the BT condition at the $p < .001$ level, and the AT condition at the $p < .05$ level.

Finally, the deviation measurement was also found to be significant across the experimental conditions, $\Lambda = .319$, $F(5,37) = 15.806$, $p < .001$, $\eta_p^2 = .681$. The post hoc results revealed that the mean deviation of the ST condition was significantly higher than those of the NT, BT, FT, and AT condition, which were all at the $p < .001$ level. Moreover, the mean deviation of the RT condition was significantly higher than those of the NT, BT, and AT conditions, which were all at the $p < .05$ level.

4.2 | Self-reported ratings

We explored the six self-reported concepts across the experimental conditions. Boxplots of the self-reported ratings are presented in Figure 6 and descriptive statistics are summarized in the supplementary material document. The statistical analysis did not reveal significant results for the emotional reactivity to the tactile feedback measurement, $\Lambda = .875$, $F(4,38) = 1.396$, $p = .253$, $\eta_p^2 = .125$.

Regarding the realism of the tactile feedback, the statistical analysis revealed significant results, $\Lambda = .336$, $F(4,38) = 18.711$, $p < .001$, $\eta_p^2 = .664$. Post hoc results revealed that the mean rating of the AT condition was significantly higher than that of the ST, BT, and FT conditions, which were all at the $p < .001$ level. Moreover, the mean rating of the RT condition was significantly higher than those of the ST and BT conditions, which were all at the $p < .001$ level, and the FT condition, which was at the $p < .05$ level.

The emotional reactivity to the virtual crowd measurement was also significant across the experimental conditions, $\Lambda = .496$, $F(5,37) = 7.515$, $p < .001$, $\eta_p^2 = .504$. Post hoc results revealed that the mean rating of the ST condition was significantly lower than those of the NT and AT conditions, which were all at the $p < .05$ level. Moreover, the mean rating of the BT condition was significantly lower than those of the NT and AT conditions, which were all at the $p < .001$ level.

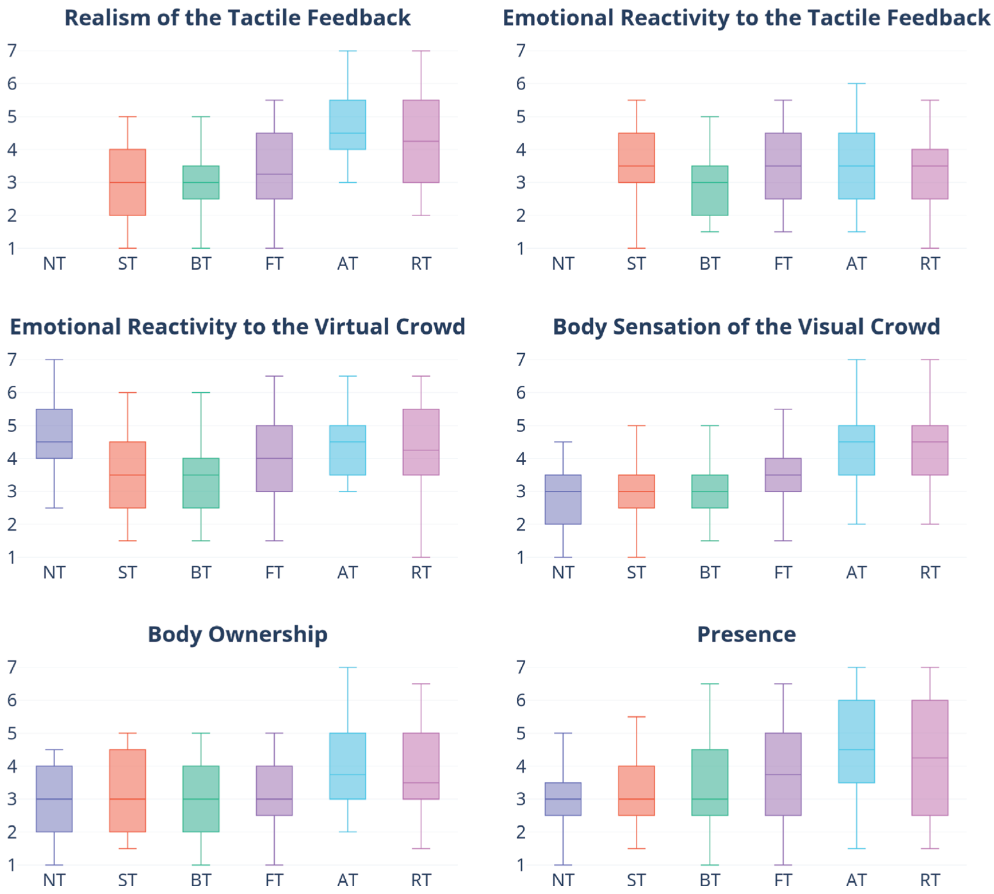

FIGURE 6 Boxplots of the participants' self-reported ratings. Boxes enclose the middle 50% of the data. The median is denoted by the thick horizontal line. See the supplementary material for means and standard deviations

The statistical analysis revealed significant results for the body sensation of the visual crowd measurement, $\Lambda = .245$, $F(5,37) = 22.793$, $p < .001$, $\eta_p^2 = .755$. Post hoc results revealed that the mean ratings of the AT and RT conditions were significantly higher than those of the NT, ST, and BT conditions, which were all at the $p < .001$ level. Moreover, post hoc results also revealed that the mean ratings of the AT and RT conditions were significantly higher than that of the FT condition, which were both at the $p < .005$ level.

The body ownership measurement was also significant across the experimental conditions, $\Lambda = .523$, $F(5,37) = 6.746$, $p < .001$, $\eta_p^2 = .477$. Post hoc results revealed that the mean rating of the NT condition was significantly lower than that of the AT condition at the $p < .001$ level and the RT condition at the $p < .05$ level. Moreover, the mean rating of the ST condition was significantly lower than that of the AT condition at the $p < .05$ level

Finally, regarding presence measurement, significant results were found across the experimental conditions, $\Lambda = .435$, $F(5,37) = 9.870$, $p < .001$, $\eta_p^2 = .565$. Post hoc results revealed that the mean presence rating of the AT condition was significantly higher than that of the NT condition at the $p < .001$ level, the ST condition at the $p < .005$ level, and the BT condition at the $p < .001$ level. Moreover, the mean presence rating of the RT condition was significantly higher than that of the NT condition at the $p < .001$ level and the BT condition at the $p < .005$ level.

5 | DISCUSSION

An experimental study on the effects of tactile feedback during immersive crowd interaction was conducted. Several interesting results were revealed from several movement behavior measurements and self-reported ratings. The effects of tactile feedback on the walking movement of the study participants were first examined while they were surrounded by a virtual crowd that was walking toward the opposite sidewalk in a virtual metropolitan city. The movement-related measurements of participants were used to understand whether and how six different experimental tactile feedback conditions could affect the way that our participants decided to perform the requested task (RQ1).

We found significant results associated with the speed of the participants as they walked across the virtual crosswalk. Remarkably, the tactile feedback that was generated at the front of the tactile vest had a significant impact on the participants' speed compared with the no tactile feedback condition and the tactile feedback that was generated at the back or the side of the tactile vest. Given that there was no significant difference between the no tactile feedback condition and the back tactile feedback condition, it was possible to conclude that the front and side tactile feedback conditions were responsible for slowing down the speed of participants when crossing the virtual crosswalk. Interestingly, we also found significant results between the random tactile feedback condition with the no tactile and back tactile conditions. Since participants were immersed in a high-density crowd of people, it was evident that it might not have been possible for them to judge whether the tactile feedback was from an actual collision with a virtual character is it was random. This unawareness worked as a pseudosensation[71] that fooled our participants that the tactile feedback during the random condition was not random. Instead, it was interpreted by the participants as tactile feedback that resulted from collisions with virtual characters.

Furthermore, significant results were found for the length and deviation measurements. Specifically, both the side and the random tactile feedback conditions affected the length of the trajectory and consequently the path that participants followed. Taking the results of the ANOVAs for both length and deviation together, it was possible to infer that the higher length resulted from the participant's decision to deviate from the straight path and reach a different horizontal position on the opposite sidewalk compared to their initial horizontal position. The side tactile feedback condition evidently worked as a force that caused our participants to move toward the left or right side, and therefore, they deviated from their initial horizontal position as they reached the opposite sidewalk. Regarding the random tactile condition, it appeared that such tactile feedback tended to confuse our participants because the visual and tactile stimuli were not synchronized. This mismatch between the two stimuli may have simply served to distract our participants.[72] It is important to note that none of the participants were aware of which tactile feedback condition was being applied, and none of them knew that the tactile feedback was randomly generated. Our participants might have believed that the tactile feedback was caused by collisions with virtual characters. Therefore, our participants decided to deviate from their straight path, while they also attempted to avoid collisions with virtual characters, which they thought that such an action could eliminate the tactile feedback.

The duration measurement was also significant. By considering speed and length measurements, such results were not thought to be unexpected. The duration results showed that the tactile feedback generated on the back of participants forced them to move faster, and participants, therefore, required less time to reach the opposite sidewalk. By contrast, the tactile feedback generated on the front side of the vest forced participants to move slower, which led to a need for more time to reach the opposite sidewalk. On one hand, when the back tactile feedback condition was applied, our participants felt that the virtual characters located behind them were pushing them, and they thus decided to move faster to avoid being pushed. On the other hand, when the front tactile feedback condition was applied, our participants did not want to be in contact or collide with the virtual characters walking in front of them. Thus, they decided to move slower to avoid colliding with the characters in front of them.

The statistical analytical data did not reveal significant results for the smoothness measurement. An interpretation for smoothness was that our participants tended to perform similar movements under all the experimental conditions. In addition, considering that the captured motion of participants was based on the tracking functionality of the VR headset, such devices provide fairly smooth motion tracking[73,74] due to the implemented tracking algorithms that smooth out the movement of the users. In this study, the missing significant results were likely due to the simple task that participants were asked to perform, the device used to capture the participants' movements, or both.

Concluding with the movement behavior measurements, it should be noted that no significant results for the direction measurement were found. Regarding this, we would like to give the following interpretation. Our participants tended to follow similar paths as they were crossing the virtual crosswalk across the experimental conditions. Even if the participants deviated when the side and random tactile conditions were applied, such deviations did not occur because our participants changed their direction. Instead, they decided to change their step width while moving toward a near-forward direction. However, since we did not capture the participants' full-body motion, it is not possible to verify our hypothesis regarding the step width, which will likely be considered in one of our future studies.

To further understand how our participants perceived the tactile feedback provided across the experimental conditions, self-reported ratings regarding various concepts were collected (RQ2). Regarding the realism of the tactile feedback and the body sensation of the virtual crowd, our participants perceived their interaction with the virtual crowd to be more realistic. They also reported feeling that the crowd was composed of more real people during the accurate and random tactile feedback conditions compared to the side, back, and front conditions. Based on these results, tactile feedback that is considered accurate and tactile feedback that cannot be distinguished by participants can affect the realism of an immersive interaction with a virtual crowd, while it also made participants feel that their interaction with the virtual crowd provided the sensation of interacting with real people.[7]

The results related to emotional reactivity to the tactile feedback were also interesting. Our participants rated the five tactile feedback conditions fairly consistently, which indicated that regardless of whether tactile feedback was considered accurate, it could still affect the emotional reactions of our participants in similar ways. Contrarily, the results of emotional reactivity to the virtual crowd were significant. We found that the side and back tactile conditions had less of an effect on the participants' emotional reactions compared with the no tactile feedback and accurate tactile feedback conditions. On one hand, the results regarding the accurate tactile feedback were somewhat expected because accurate tactile feedback provided the illusion that participants were part of the virtual crowd. Notably, a prior study regarding tactile feedback indicated that their participants were more sensitive to logical (accurate) tactile feedback compared to one that is illogical (inaccurate or random).[7] On the other hand, the results regarding the no tactile feedback condition could not be considered as expected. Results suggested that less accurate tactile feedback might have less of an effect on the emotional reactions of participants compared with no tactile feedback. It is also possible that our participants might have been expecting a tactile sensation during the nontactile feedback condition, and this expectation might have caused an increased emotional reaction from our participants.

Regarding the self-reported ratings, when assessing the self-perception of participants (body ownership and presence), both the accurate and random conditions were rated higher compared with no tactile feedback and back tactile feedback conditions. These findings complement the findings regarding the realism of tactile feedback and the body sensation of the virtual crowd. Participants were evidently sensitive to their bodies, even when they were placed within the virtual crowd without a self-avatar to represent them. This finding was consistent with prior work that investigated the effects of tactile feedback on body ownership.[59,60] Additionally, the significant results for participant presence were also consistent with prior work that associated participants' sense of being in a virtual environment with the provided tactile feedback.[55,56] Thus, when the tactile feedback is considered to be accurate, or when participants cannot judge the accuracy of the tactile feedback, which was the case for the random tactile feedback condition, the inability of participants to distinguish the inaccurate tactile feedback affected the self-perception of participants in a positive way, that is, the participants rated higher their sense of body ownership and presence during the random and accurate tactile feedback conditions.

Apart from the collected data, some of the participants' comments regarding their experience with the tactile feedback and the developed applications are worth mentioning. Many participants reported that they were very impressed with the positive change in their overall experiences when tactile feedback conditions were included compared with the no tactile feedback condition. A few participants also reported that there were periods when they felt the crowd was actually surrounding them. Others mentioned that they liked the idea of using tactile feedback to sense nearby characters, but they also expected visual effects that simulated their body shaking when they collided with the characters. Many participants told us that they would like to see a self-avatar that represented them in the virtual environment because such an avatar could have helped them avoid colliding with the virtual characters. A couple of participants told us that the lack of tactile feedback being applied to their lower body made the experience feel somewhat less realistic. Finally, none of the participants complained about the weight of the tactile vest (2.75 kg) and the backpack computer (3.6 kg), and all of them reported that the equipment was comfortable to wear them, and it was easy to walk with the gear attached to their bodies.

In addition to the interesting findings discusses in this section, we did identify certain limitations that should be considered by researchers who may seek to conduct additional studies in this area of VR research. The first limitation is related to the representation of participants in the virtual environment. We decided not to represent participants with a virtual body within the virtual environment for two reasons. First, we realized during the preliminary experimentation process that it was difficult to attach the inertial motion capture system to participants (especially the upper piece) because participants were wearing the tactile vest and backpack computer. While others have found that self-representation[25] and movement artifacts[75] affects the movement behavior of participants, the inclusion of a representative body in this experiment could be beneficial because participants would not only sense a collision with a virtual character, but they could also see the collision. Thus, with an optical motion capture system, it may have been possible to capture the full-body motion of participants and use an avatar to represent them. A second limitation is that we examined conditions related to the position of the tactile feedback without including duration and intensity variations. To further understand the effects that tactile feedback may have on movement behavior and self-reported ratings, investigating additional tactile feedback conditions that include both duration and intensity variations seems imperative.

Despite the previously mentioned limitations, considering the results of movement behavior and self-reported ratings together, our participants were evidently sensitive to tactile feedback conditions. Both their movement behavior and their self-reported ratings differed across the experimental conditions, and most differences were found to be associated with accurate and random tactile feedback conditions. The results revealed that when our study participants were immersed in a high-density crowd simulation, they became sensitive to tactile feedback; however, they were not able to distinguish between accurate and random feedback. A virtual environment that was crowded with virtual characters made it difficult for our participants to judge whether random tactile feedback was accurate. Therefore, they were evidently not able to distinguish the mismatched stimuli. This contradicts the findings reported in various other studies concerning mismatched stimuli[76,77] and studies indicating that accurate or logical tactile feedback makes the interaction more realistic compared with illogical tactile feedback.[7,78] However, considering that most of the prior studies that we reviewed provided more discrete visual and haptic interaction compared with this study, our results have gone a step further. More specifically, they showed that when participants cannot distinguish the individual components of the visual information they receive, which included the collisions with the virtual characters in our virtual crowd, participants could perceive inaccurate tactile feedback as realistic.

6 | CONCLUSIONS AND FUTURE WORK

This study was conducted to investigate the impact of tactile feedback on participants' movement behavior and self-reported ratings as they were exposed to different conditions. The collected data revealed a number of interesting results that indicated different tactile feedback conditions could indeed affect both the movement behavior and the self-reported ratings of participants. These results are particularly valuable for future research and development of VR interactions that occur within a virtual crowd of people when different tactile feedback conditions are applied. Parts of our results could be considered by VR application developers who are seeking to immerse VR users within moving crowds of people.

In addition to the previously mentioned limitations that require further experimentation, we are planning to conduct additional studies concerning the effects of tactile feedback on participants walking in immersed VR scenarios. Specifically, we are planning to conduct VR studies for the evacuation of buildings, VR interactions in extreme weather conditions and natural disasters, such as earthquakes and hurricanes. We believe that such studies will improve our understanding of how humans perceive and interact with virtual environments, virtual characters, and tactile feedback, while they can also be used to refine such interactions to make them feel more realistic. By understanding how participants interact with such events, it may be possible to provide instructions and design guidelines for the research community. Developers will then be able to develop more believable interaction scenarios, such as training applications in which humans learn how to react (e.g., evacuation or extreme weather conditions). Virtual reality is a powerful tool that has proven effective in helping to better understand human behavior in a number of different simulated scenarios. Such technology could be quite beneficial for future studies because there is no need for humans to face real-world challenges, which can effectively eliminate serious safety risks.

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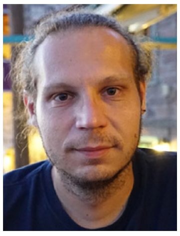

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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