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Reference:

Peeters Thomas, van Breda Eric, Saeys Wim, Schaerlaken Evi, Vleugels Jochen, Truijen Steven, Verwulgen Stijn.- Vibrotactile feedback during physical exercise : perception of vibrotactile cues in cycling
International journal of sports medicine - ISSN 0172-4622 - 40:6(2019), p. 390-396
Full text (Publisher's DOI): https://doi.org/10.1055/A-0854-2963
To cite this reference: https://hdl.handle.net/10067/1588960151162165141

Vibrotactile Feedback during Physical Exercise: Perception of Vibrotactile Cues in Cycling

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The manuscript ID is IJSM-08-2018-7176-tt.

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Abstract

The aim of this study was to investigate the perception of vibrotactile signals during physical exercise by comparing differences in recognition between stationary and cycling positions. The impact of physical exercise on the ability to perceive vibrotactile cues is unknown, whereas the recognition in stationary position has been shown previously. Vibrating elements were positioned at three locations on the thighs and spine of nine athletes to apply various vibrotactile cues. Subjects performed at 0%, 50%, 70% and 90% of their maximal cycling power output and denoted the interpretation of the vibration signals on a touchscreen. The results show a similarity in correct recognition between stationary position and physical exercise for the thighs and spine ($p > 0.1$) and demonstrate a decrease in response time for 70% and 90% levels of physical exercise compared to 0% and 50% ($p < 0.001$). Furthermore, vibrotactile signals at the spine are noticed more accurately and more rapidly compared to the thighs ($p < 0.01$). These results suggest that vibrotactile feedback also has potential in applications during physical exercise. The potential use of vibrotactile feedback can be in cycling for, among other, correcting the aerodynamic position. Applications in other sports and health-related domains are feasible as well.

Keywords: haptic perception, vibrotactile feedback, physical workload, cycling, tactile illusions

Introduction

Auditory and visual senses are mainly used for instructing subjects on how to perform movements. However, in situations where communication is hampered, e.g. in noisy and busy environments such as in sports, it can be an added value to replace, complement or amplify auditory and visual instructions by vibrotactile signals. Applying vibrotactile cues is an additional and interesting opportunity for communicating motion related instructions through haptic cues [9,13,16]. The activated vibration signals on the subjects' skin can be used for either posture or movement adjustments [19].

Vibrotactile cues can provide additional sensory information in a broad number of domains ranging from leisure activities to life-saving tools [7,12,15]. In these studies, there is a considerable variation in types of vibrotactile signals. Vibrotactile cues were mostly applied as veridical signals, varying in frequency and intensity [1]. Additionally, Lee [11] demonstrated the existence of vibrotactile illusions, which are known as perceived vibrating signals or patterns not directly caused by vibrating elements (tactors). Vibrotactile illusions are divided into two types: 1) sensory saltation, where a signal travels between two or more tactors which are activated at different time intervals or 2) funneling, where the tactor signal is perceived in the middle between two simultaneously activated tactors [10,11]. Both sensory saltation and funneling have the potential to reduce the number of tactors required to give one instruction.

Most research concerning the perception of veridical and illusory vibrotactile cues has been performed in stationary settings where the subjects' movement and physical effort is limited. Vibrotactile guidance has great potential in active sports settings as well [19]. However, only a limited amount of studies reported on the effect in subjects performing physical exercise such as running [6], rowing [17], snowboarding [18], skating [8] and tennis [14]. For instance, the usability of vibrotactile feedback in technique and posture optimization in sports has been shown [8,14,17,18]. Hasegawa [6] used vibrotactile feedback for instructing running directions and confirmed accurate recognition of vibrotactile patterns in standing still position and during low speed running (≤ 10 km/h), but noticed difficulties in the perception of vibrotactile cues during high speed running (+/- 15 km/h).

Cycling has also considerable application potential for using vibrotactile feedback. For instance, the most efficient aerodynamic and biomechanical cycling position is hard to maintain during intense physical exercise. Vibrotactile signals would be an elegant method to verify and correct aerodynamic cycling positions during training and racing [3–5,20]. To apply vibrotactile feedback in intensive sports as cycling, the exact impact of the level of physical exercise on the perception of vibrotactile cues should be known. Therefore, the aim of the present study is 1) to unravel the perception of vibrotactile signals during cycling and 2) to investigate whether or not illusionary signals also occur during physical exercise.

Materials and methods

Participants

The study has been approved by the combined Ethical Committee of the University Hospital Antwerp and University of Antwerp (reference: B300201629562). An informed consent was obtained from all subjects. Ten well-trained amateur cyclists were recruited from the community of the University of Antwerp, Belgium. All subjects reported normal visual acuity and normal vision.

Apparatus

A configuration of six wireless controllable tactors as in Figure 1a was developed. The tactors can be activated separately or in combinations using an Arduino Feather 32u4 Bluefruit LE and HC-12 module. An 850 mAh Lithium Ion Battery powers the tactors. Two Applications were acquired to provide vibration signals in random order, one for the thighs and one for spine measurements.

In the Application, 16 vibration signals were defined (a-p in Table 1), including veridical and illusion signals, which last one second each. Table 1 shows the used signals for thighs and spine. Signals a, c and e to h represent one-second continuous veridical signals at one location. Characters b and d are one-second signals at upper and lower locations simultaneously, which serve as the funneling illusion. Next, i to p are saltation signals, which indicate a movement along the segment. Signals i to l are movement saltation signals and activate three tactors in a row and signals m to p describe saltation illusions, where only the two outer tactors are triggered using a specific time delay according to Lederman and Jones (2011) as clarified in Table 2 and in the supplementary materials.

A touchscreen, which displays an image of the thighs (Figure 1b) or of the spine in the same position as the subjects are on the bike, was positioned in front of the subjects (Figure 1c) and used to indicate where the subjects experienced the signal immediately after observation.

Procedure

Stationary position and 50%, 70% and 90% levels of physical effort were standardized relative to subjects' maximal power output using a Cyclus2 ergometer. The power output (Watt), cadence and test time were registered continuously. The protocol started with an initial workload of 75 W, followed by an individual increase of 0.5

W/kg body weight every 3 minutes, until exhaustion. In the experiments, 0%, 50%, 70% and 90% of the maximum power output were used to allow standardized comparisons between subjects.

Selection of vibrations. Afterwards, the perception of vibrotactile signals was investigated on the thighs and on the spine in stationary position and during the different levels of cycling exercise. Subjects 1 to 5 started with vibrotactile experiments on the thighs, whereas subjects 6 to 10 started with vibrotactile signals on the spine. For both the thighs and spine experiments, the order of levels of physical effort was identical: starting from stationary to 50%, 70% and 90% of the individual maximal power output. Within these eight experiments per subject, the sequence of the vibration signals was randomly generated. Identical technical setup was used for both thighs and spine experiments.

Thighs. Three tactors per thigh were placed directly on the skin and adjusted to optimal placing with tape and Velcro strips (Figure 2). The distance from the center of the patella to spina iliaca anterior superior (SIAS) was measured (Figure 2a) and the tactors were positioned at 1) $4/20^{th}$ of that distance, just above knee cavity to avoid annoyance during cycling, 2) at $14/20^{th}$ of the distance, the highest possible position under hip joint center and 3) at $9/20^{th}$ of the distance, in the middle of the former two placements. The tactors were placed in the middle of the thigh in the sagittal plane for both the left side as well as for the right side.

Spine. Similar experiments were repeated for the spine. Three tactors were placed using the distance between processus spinosus C7 and spina iliaca posterior superior (SIPS) (Figure 3a). The elements were positioned at C7 and SIPS and exactly in between in the middle of the spine in the sagittal plane. All signals were applied twice (Table 1) to obtain the same number of vibrations and the same testing time for all experiments. The three remainder tactors were not used in this section. Again, subjects were asked to specify the perceived signals on the touchscreen (Figure 3b).

Subject response setup. When a vibrotactile cue was applied, a green square lighted up, which disappeared immediately after the subjects had responded. If a square turned red, the experiment was finished. The various buttons in the Application gave all potential locations of the vibrations. The arrows indicated signals which were moving along the segment. The “no signal” button should have been selected when the subject did not feel any vibrating signal during the time the square was highlighted in green. “Signal at another place” signified a signal at another place than the options on the screen. Finally, “more places” could be denoted when the subject felt signals at various locations simultaneously. Signals were applied 20 seconds after the previous answer was denoted by the subject and continued until all 16 signals were provided. The duration of one test session lasted six minutes. The participants were instructed to keep the imposed wattage during the entire protocol with a cadence between 70 and 100. In between two test conditions, the participants got two minutes of rest.

Overall design. In order to exclude potential learning effects, a test where the 16 different vibration signals on the thighs were activated was performed after the initial ergometer test. Subjects were asked to denote where vibration signals were observed on the touchscreen while seated in a normal chair. Six days after the ergometric test, the perception tests for the thighs and spine were performed. Detection thresholds for perceiving vibrotactile signals were mapped for various levels of physical effort. The correctness of recognition as well as the response time, which is the time needed to denote the answer on the touchscreen after the signal has been applied, was recorded for all signals. The response time was measured from the moment the green light turned on until the participant touched the screen. The touchscreen position was adjusted to the handlebar height and was in line with the position of the brake hoods to ensure each participant could reach the touchscreen. The dimensions of the buttons to indicate the answers were 13 x 89 mm for the saltation representation and 24 x 28 mm for the other ones.

Statistical analysis

For both the thighs and spine, four experiments consisting of 16 vibration signals each were performed for the nine subjects. A total of 1152 vibration signals were included to analyze the correctness of the experienced vibrating signals and the influence of the response time.

Perception in stationary position. Differences in recognition percentage between veridical and movement saltation on the one hand and funneling and saltation illusion signals on the other hand were statistically analyzed using the McNemar’s test. Funneling illusion was expected to be sensed in the middle of both outer tactors and was compared with recognition percentage of the middle signal. Acceptance ratio of movement saltation was compared with these of the saltation illusion signal.

Perception during physical exercise. Cochran Q’s test was used to detect differences in correctness between stationary and dynamic experiments at 50%, 70% and 90% of the maximal power output for the thighs as well as for the spine. Similarly, effects on response time between various tests were examined using Friedman-test. Wilcoxon test and Bonferroni correction were executed when needed.

Thighs versus spine. Differences in perception on the thighs and spine were investigated using McNemar for correctness and Wilcoxon for response time. Similar statistical tests were carried out to detect differences between recognition on the left and right thigh.

Results

Well-trained amateur cyclists (6 male and 4 female; age M = 22.4 years, SD = 3.3; weight M = 68.1 kg, SD = 11.3; cycling experience M = 8.1 years, SD = 5.3; cycling load M = 9.8 hours/week, SD = 5.3) were included in the study. One subject was not able to participate in one of the experiments due to illness and was excluded from all analysis. Three measurements out of the 1152 data points were excluded from the analysis due to technical/human errors (subject failed to touch firm enough on the touchscreen, loosening of one of the tactors during the experiment or providing a wrong signal by one of the researchers).

Sample size calculations revealed that a sample of eight subjects would be sufficient to detect a difference, between veridical and illusion techniques as well as between stationary position and physical exercise, with statistical power 0.80 and type I error probability 0.05.

Perception in stationary position

Table 3 shows the percentages of correct interpretations in stationary position on the thighs and spine per applied signal. McNemar's test indicates that there is a significant lower correct observation for funneling and saltation illusions compared to veridical and movement saltation signals ($p < 0.001$).

Perception during physical exercise

Table 4 shows the effect of the different levels of workload on the percentages of correct recognition. The percentage of correct answers and response time of the stationary position was compared to the outcomes for 50%, 70% and 90% of the maximal power output. In this table, the funneling and saltation illusion conditions were excluded. The Cochran Q test indicates that the level of workload has no influence on the number of correct answers for the thighs ($p = 0.14$) and spine ($p = 0.91$). The study states that there are significantly faster response times for 70% and 90% of physical exercise compared to 0% and 50% for both thighs and spine ($p < 0.001$) with an effect size of -6.8.

Thighs versus spine

The variation in perception between the thighs and spine was analyzed using McNemar statistical test for intra-individual comparison. The test indicates that the correctness of interpretation is significantly higher at the spine compared to the thighs (spine 59.4%, thighs 53.0%, $p < 0.01$). Also, the response time improves for spine experiments with a quicker response time of 453 ms compared to the thighs (spine M = 889 ms, SD = 537, thighs M = 1342 ms, SD = 1248, $p < 0.001$). Furthermore, vibrations are better recognized at the right thigh compared to the left thigh (right thigh 58.3%, left thigh 47.7%, $p < 0.001$). Six of the participants exhibit a higher perception percentage at the right thigh. However, there is no difference in response time between signals on the left and right thigh ($p = 0.12$).

Discussion

The most important finding of the present study is that vibration signals are, in contrast to the scarce literature, well perceived during physical exercise for both thighs and spine. In the present study, various veridical and illusion signals were applied on the thighs and spine during different workloads on an ergometer. This is, to the best of our knowledge, the first study that 1) describes the effect of physical exercise as an explicit variable affecting the perception of vibrational signals and 2) investigates the convenience and robustness of vibration signals during physical exercise.

Verification of the state of the art

The results show that veridical signals at the spine are consistently perceptible in stationary position. For the thighs, vibrations at the knee (lower) are best perceptible. Also, the middle signal on the thighs has a perception frequency higher than 80% [10]. Vibrations at the higher end of the thigh (under hip joint center) are clearly less perceptible than other veridical signals, which can be explained by a usual higher fat and muscle mass.

For both thighs and spine, the movement saltation signals where three tactors were activated in a row are less recognizable as veridical signals (< 80%). Saltation illusions where only the two outer tactors were triggered using the specified time delay (Table 2) are even less perceptible (< 50%). Funneling illusions are almost not observed by the subjects. Funneling illusions were usually interpreted as more signals instead of one signal in the middle of the segment, where saltation illusions were occasionally understood as more signals or as one of the activated elements. In contrast with the findings of Lederman & Jones, illusions are significantly less perceptible as compared to veridical signals [10]. An explanation for this is not easy to provide but illusion signals as used in literature were applied on the fingertips, forearm, shoulder or thigh with a maximal space of 8 cm in between two tactors [10,11,18]. The minimal distance between two tactors in our study was 11.5 cm. Furthermore, the low recognition percentages of illusions remain present during physical effort. We cannot exclude that illusion signals as used in literature would be present in our experiments, but in order to reduce the number of tactors from a practical point of view we had decided to increase the distance between the tactors. Nevertheless, most posture and movement guidance by vibrotactile information is achievable with three tactors per segment as used in the present study.

Perception during physical exercise

The most interesting outcome of this study shows that vibration signals are perceived during both physical exercise as well as in stationary position. This is in contrast with the findings of Hasegawa & Shinoda [6] who observed difficulties in perception during intensive running. For both thighs and spine, we found a significant decrease in response time, without decrease in correctness of recognition, at the 70% and 90% level of maximal workload in comparison with 0% and 50%. It is well known that during intense physical exercise the levels of adrenaline increase which could improve the response time of subjects [2].

Thighs versus spine

Another interesting finding of the present study is that indicating correct answers on the touchscreen was more difficult for the thighs compared to the spine. One possible explanation could be that the increased number of choices on the touchscreen (left and right part) caused increased cognitive decision time. Furthermore, the thighs were in constant motion during the tests, where the spine is bonier and less moving during cycling. The increased response time for thigh tests confirms these findings.

The difference in recognition between left and right thigh cannot be declared by extra factors as left and right handedness of the participants. The higher perception percentage on the right thigh could be a coincident outcome caused by the small sample size for this comparison.

Conclusion and future research

This study investigated the effect of physical exercise on the perception of vibrotactile cues consisting of veridical and illusions signals. Vibrotactile signals at the thighs and spine are perceivable in stationary position but also during diverse levels of physical effort at 50%, 70% and 90% of the maximal power output. Furthermore, the vibration signals are more rapidly recognized at 70% and 90% of the maximal power output as at 0% and 50%. Our outcomes provide more opportunities for the use of vibrotactile feedback during physical exercise in various application domains. A primary application for such vibrotactile system is in sports in general and cycling in particular. It could be used as training aid for enhanced power output by remaining in the optimal aerodynamic position. Alternative applications in various domains such as rehabilitation are also feasible. Vibrotactile feedback in combination with motion capturing has considerable potential in posture and movement steering.

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Graphics legend

Figure 1. a) Tactors to be applied onto subjects’ skin. b) The touchscreen where thighs are depicted in cycling position in top view and subjects can denote where they observe the vibration signals. The arrows on the image indicate movement signals. Furthermore, subjects can also denote that they do not observe any signal, observe a signal at another place or at more locations. c) The complete test setup, where the bike is positioned on the Cyclus2 ergometer with the touchscreen in front of the subject.

Figure 2. Attachment of the tactors on the thighs. a) The measurement of the patella-SIAS distance to indicate where tactors should have been placed. b) Tactors were firmed on these locations using tape. c) And an extra fixation of the tactors was applied using Velcro.

Figure 3. Procedure of the spine experiments. a) The distance between the processus spinosus C7 and SIPS was measured to indicate where tactors should have been placed. b) The touchscreen where the spine is depicted in cycling position in top view and subjects can denote where they observe the vibration signals.

Table 1: Description of the 16 signals used in the experiments for thighs and spine, applied in random order.

Table 2: Movement saltation and saltation illusion signals, where A represents the first tactor, B the middle and C the last one (see also supplementary material).

Table 3: Percentages of correct recognition in stationary position for thighs and spine.

Table 4: Percentages of correct recognition and average response times with respective standard deviations per level of physical exercise for the vibration signals on the thighs and spine. The funneling and saltation illusion conditions were excluded.