Drone-Driven Running: Exploring the Opportunities for Drones to Support Running Well-being through a Review of Running and Drone Interaction Technologies

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ABSTRACT

There is an underexplored interaction space for drones that can be utilised as running interaction technology, distinct from human drone interaction that warrants foregrounding. This paper consolidates the current state of art in running interaction technology through a review of relevant studies and commercial technologies in a framework positioned using dimensions related to the form of interaction as identified in the sports ITECH framework. Our analysis highlights the unmet opportunities in running interaction technology and presents the potential of drones to further support runners. The potential of drones to support various forms of interaction are supported using exemplar research done in human-drone interaction. Through our findings, we hope to inform and expedite future research and practice in the field of running interaction technology and runner drone interaction by supporting researchers in defining and situating their contributions.

CCS CONCEPTS

• Human-centered computing → Interaction design theory, concepts and paradigms.

KEYWORDS

Literature Review, Running, Drone, Running Interaction Technology, Human Drone Interaction, Runner Drone Interaction

ACM Reference Format:

1 INTRODUCTION

The field of sports interaction technology (SIT) is burgeoning with a multitude of technologies being used for all possible purposes in the sports and health domains [97]. An oft-researched domain within this field is the use of technology to augment or support running activities [42, 50, 57, 59]. Existing works in the sub-field of running interaction technology (RIT) have demonstrated the potential of various interactive technologies to serve a multitude of running purposes, offering valuable design knowledge for the form and functionality of the interactions supported by these technologies [42, 50, 51, 58, 98, 106, 114]. This also stays true to the work in the field of human drone interaction (HDI) that utilize drones to support running activities. Existing works in human drone interaction (HDI) serve as a paradigm for the potential of drones to support runners and its ubiquity in the near future [13, 48, 82, 110]. Inspired by the application of drones in various domains [118], there has already been work done in this even more niche field we define as runner drone interaction (RDI). However, the existing body of work in RDI [11, 78, 82, 103, 110], while presenting valuable challenges and insights, also risks repetition and saturation of knowledge due to cumulative effect [13]. This may pose difficulties for researchers seeking fresh inspiration and innovative ideas for meaningful drone interactions in running. This motivates the need to consolidate the existing work in RIT into a framework that uncovers untapped opportunities, and motivates future RIT researchers.

To meet this need, we analyzed and organized existing work in running technology, covering commercial and scientific efforts. To organize the identified corpus of works, we use the sports ITECH framework as introduced by Postma et al., which recognizes the interplay between the form and function of the interactions supported by technology [97]. In our analysis, we primarily use ‘form of interaction’ dimensions to categorize these works. We specifically focus on these than the function dimensions because we recognize that while numerous functions can be envisioned for a technology [57–59, 61, 82, 110], it is crucial to first comprehend the feasible forms of interaction. By categorizing earlier works by their forms of interaction, we gain a deeper understanding of the available options and opportunities. This helps us develop realistic and grounded functions aligned with the forms of interaction. Moreover, categorizing prior works based on their form of interaction would unveil unexplored repertoire of functions for the technologies used in those works. By prioritizing the analysis through the form dimensions, we can effectively identify untapped potential and develop meaningful advancements in the field of running technology.

In this paper, we first outline the methodology followed for reviewing and selecting works in running interaction technology (commercial and research). Next, we categorized the identified works based on the technologies central to the interactions. Next,
we positioned these works along selected sports ITech framework dimensions. This is followed by a concise overview, highlighting drones’ potential to support various forms of interactions. We discuss notable examples from HDI and RDI fields, provide suggestions for future research directions, and conclude by addressing some shortcomings in our methodology and devised framework.

2 METHOD

We compiled a corpus of related works on running interaction technology by employing approaches similar to earlier literature reviews [13], incorporating elements of the PRISMA methodology, and utilizing bibliography hacking. To identify relevant research works, we employed a combination of terms which included "(run*) AND ((tech*) OR (interact*) OR (wear*) OR (app*) OR (smart*) OR (robot))" in their titles, abstract or keywords. Additionally, we reviewed systematic and related works, leveraged prior knowledge account of earlier works in HDI, showcasing the ability of drones to noted that our intention with this work is to provide a descriptive account of earlier works in HDI, showcasing the ability of drones to support running-related activities through a structured framework, rather than being prescriptive and imposing a rigid structure on the development of drone-based running interaction technology.

3 RUNNING INTERACTION TECHNOLOGIES

Activity bands, smartwatches and similar On-Body Sensors are some of the most commonly used technologies by recreational and professional runners [73]. Most of these consist of optical sensors to measure heart rate, skin temperatures, and blood oxygen levels, and vibration motors to provide alerts. They are also Bluetooth-connected to a secondary device (typically a smartphone or pressure sensitive soles [106]) to transfer the recorded data and provide runners with further insights about the run and the strain endured by the body throughout the run. The trackers and smartwatches also track other parameters like sleep, rest, etc. which indicates recovery, i.e. how well they are adapting to body strains throughout the day. Although they serve the same function, activity bands and smartwatches differ in how they interact with runners. Activity bands use built-in motors to deliver minimal and simplistic feedback on non-complex information such as reaching a milestone or over-exertion of the body during and/or after a run. Smartwatches on the other hand additionally make use of a screen and intuitive user interfaces to communicate with the runner during and/or after the run. Intuitive user interfaces enable runners to view their data immediately after the run, rather than waiting for the data to sync to their smartphones. The built-in GPS function also assists runners in recalling their route. Interaction with these systems during the run is typically very minimal [16, 73]. These devices are predominantly used to document the athletes’ activities, notify them about deviations from their goals, and identify irregular patterns of activity [61]. However, the information required to assist a runner in preventing injuries and improving performance is significantly more sophisticated and requires real-time input that allows the runner to adjust themselves. Some of the complex information that would help determine the points of (potential) injury and provide pointers on improving running performance is information about a runner’s kinetic (the various forces acting on the lower body) and kinematic (speed, position, and angle of various lower body joints) metrics [50]. The unobtrusive bands and watches do not have the necessary sensors to record the required metrics or the actuators that will help relay real-time corrective/directing feedback.

On-Body Trackers offer more access to some of these necessary metrics. The trackers are commonly attached on the body using adhesives, or on clothing using a clip. Most of the trackers referenced in the footnotes consist of 9-axis sensors (accelerometer, gyroscope, and compass) to measure the motions of the foot/hip/trunk and derive multiple kinetic and kinematic metrics. These metrics include, but are not limited to: efficiency metrics (step rate, stride length, contact time, vertical oscillation, flight ratio, and power), shock metrics (impact and braking Gs), foot motion (footstrike type, pronation excursion, and pronation velocity), derived metrics (peak velocity, GRF, contact ratio, flight time, stride angle, leg & vertical spring stiffness, vertical GRF rate, horizontal GRF rate,

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2 www.xsens.com/xsens-dot
While most of these applications serve documentation and social purposes, some may indicate the need for change if signs of risk occur, this system alters the runner’s foot strike directly. Hassan et al. [45] demonstrate that EMS actuation of specific muscles is a more effective approach compared to simply alerting runners when errors occur, this system alters the runner’s foot strike directly. Hassan et al. [45] demonstrate that EMS actuation of specific muscles is a more effective approach compared to simply alerting runners when errors occur, this system alters the runner’s foot strike directly.

**Smart Insoles/Socks** although not widely adopted, contain pressure and other sensors that provide some insightful data about how athletes run. Using pressure sensors, IMU, heart rate sensor, and Bluetooth, the insoles and socks can track various lower leg kinetic, kinematic, and physiological metrics (ground reaction forces, footstrike, cadence, step length, balance, stability, contact time, flight time, and heart rate). The sensing occurs during the run, while the interaction with and learning from the data usually occurs after the run. The measured data can be used to derive multiple metrics, which may differ depending on the product. However, a limitation of smart insoles and socks is their inability to measure crucial factors such as lower body joint angles, which are essential for achieving an efficient and safe running stride [30].

**Smartphone Applications** are another set of commercial tools that help runners in tracking their runs and offering insights based on data collected through various sensors. The applications mentioned in the footnote suggest training schedules and provide dashboards for analyzing and enhancing running form before or after a run. Some applications offer subscription plans that connect runners with professional coaches who create/recommend workouts and nutritional plans based on tracked and inputted data. Others recommend running routes and include social features, such as sharing activity parameters, progress, challenges, and images of places visited during the run with other runners. They also allow runners to prioritize safety by sharing their live location with friends/family. While most of these applications serve documentation and social purposes, some may indicate the need for change if signs of risk are detected. However, they typically do not provide guidance on how to improve performance through these changes. Runners who become deeply involved in the social aspects of these applications may risk injury while attempting challenges set by others on social media. Additionally, most of these applications work best when paired with trackers and sensors from the same companies, putting runners who have access to third-party trackers at a disadvantage.

**Other smartphone applications help (motivate) runners to improve their pace, cadence during a run**, heart rate through glanceable information and music (TripleBeat) [22], posture (through vibrations [115]), stride form [92] or encourage physical activity for charitable causes [7]. Applications like RunMerge enhance proprioception by allowing users to review their lower body movement data recorded using various sensors after a run [64]. Currently, some applications utilize songs (PaceDJ) [8] and RockMyRun [9] and story-based narrations (Zombies Run) [10] to help runners work on their running pace or maintain their adherence to running practice [84]. Song-based pacing programs allow runners to set their own pace or utilize an external device to assess their heart rate or acceleration to calculate the BPM of their music. Narrative story-based pacing applications may help runners perform interval training or reach a target pace by following the instructions provided in the story. These methods of interaction allow runners to enjoy their run, motivate them, reduce their perceived rate of exertion, and at the same time help improve their pace [30, 60]. However, a significant flaw of smartphone applications is their inability to track incorrect running forms that runners may adopt to match song speed or directions communicated through the phone, potentially leading to injuries and decrease in performance.

**Haptic technology used in the Strive [124] system provides real-time breathing feedback based on the runners’ respiration rates.** However, the authors note that external vibrations from running outside may distract runners, making it challenging to perceive haptic vibrations and rendering the system ineffective. FootStriker [45] on the other hand provides real-time feedback through electric muscle stimulation (EMS) to enhance the runners’ footstrike technique. Instead of alerting the runner when errors occur, this system alters the runner’s foot strike directly. Hassan et al. [45] demonstrate that EMS actuation of specific muscles is a more effective approach compared to simply alerting runners about form issues. This is because runners could actively retain their acquired knowledge after the training session.

**LED Lights/Screens** in a runners’ environment or accessories are another set of tools to enable interactions. The #Wavelight [11] pacesetter system (present on a few running tracks) uses LED lights to help runners train their pace and prepare for routines and training. The information provided by the light is present in the runner’s line of sight, and when programmed correctly, the light provides the right motivation for the runner. The #Wavelight is a great example of communicating pace using simple visual cues without overloading their cognitive load. In the temporary public Nike Unlimited Stadium installation, virtual avatars were projected onto large LED screens alongside the track to help runners in improving their pace. A glance at the screen allows runners to track their speed and lap count enabling them to compare their time with others. GraFeet by Woźniak et al. [135] and Shoe Integrated Displays by Colley et al. [20] provide feedback to wearers through LED lights embedded in

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6 www.pacedj.com/, www.rockmyrun.com/, www.zombiesrungame.com/, but also see RunningCoach [5], RunBuddy [44], and PaceGuard [33]
7 www.charitymiles.org/
8 www.pacedj.com/
9 www.rockmyrun.com/
10 www.zombiesrungame.com
11 www.wavelight.live/
12 See the description at www.harbtlebogleegarty.com/nike-unlimited-stadium
their shoes. The LED lights on the outsole of GraFeet [135] shoe help runners visualize pronation, foot strike type and impact Gs post-run. The shoe integrated display [20] have LED strips along the toe and tongue of the shoe to indicate whether runners are below, at or above a pre-set pace using various colours. Howel by Genç et al. [37] shows the usage of soft wearables and ambient displays to display heart rate zones. The Social Fabric Fitness device by Mauriello et al. [77] show how LED screens/E-ink displays can be embedded in textiles to display information about distance, pace, duration and heart rate to mediate information exchange during group running. Although these interaction forms can boost runners’ motivation and facilitate post run reflections they do not provide guidance on how to run for performance improvement and injury prevention.

Virtual/Augmented Reality tools were also utilized to enhance running experiences. VRRun [137] aims to increase exertion, enjoyment, and motivation by gamifying real-life movements, detected by a smartphone’s accelerometer, and mapping them into actions performed by characters in the virtual world displayed on the phone. However, this system confines users to running in place since it solely detects changes in the vertical direction. Similarly, Ioannou et al. [54] developed an interactive virtual reality system that tracks and augments users’ run and jump movements in the virtual environment, demonstrating how this might enhance intrinsic drive and perceived competence. However, if not used in a safe environment, such VR systems can decrease the user’s awareness of the physical world thereby making VR systems more restrictive to use during exertion activities [26, 128]. While augmented reality (AR), exemplified by Hamada et al. [43], can enhance the running experience by overlaying virtual elements onto the real world to help users set their pace, it’s worth considering that constraints on user location and movement freedom may still affect the sense of naturalness during a run. Furthermore, since these systems do not detect potential injuries or provide guidance for healthy runners to run efficiently within the virtual world, these could potentially pose long-term health risks to users [26, 128].

Audio based technology has been employed in several systems to enhance running experiences. “Run, Beep, Breathe” van Rheuden et al. [126] utilizes auditory feedback to guide runners in their breathing technique during a run. The authors examine the effectiveness of sound effects compared to metronome sounds, as well as the differences in efficacy between training sessions and regular running routines. ’Keep the Beat’ [12] employs auditory feedback through conversation and beeps to assist runners maintain their cadence while running. Some works have explored the use of music. Lorenzoni et al. [72]’s system provided auditory feedback, combining noise with music, to help modify step rate based on accelerometer data. The RunnerPal system [41] recommends music to help users achieve target heart rate values by analyzing breathing rhythms, heartbeats, and strides using peripheral devices. The MPTrain system [94] employs physiological sensors to detect heart rate and suggests music to help runners adjust their pace to reach target heart rate zones. den Berghe et al. [24] developed a system that combines music and noise with tibia shock to help runners understand and reduce the shock they experience. While these studies demonstrate the effectiveness of simple audio cues or cues combined with music in adjusting certain aspects of a run while maintaining flow, their simplicity poses a challenge when providing feedback that requires explicit instructions for running adjustments. This challenge becomes particularly significant for novice runners who may misinterpret audio cues with improper context, potentially leading to incorrect running techniques and increased risk of injuries.

Motion Capture System like Qualisys 13 use high frame rate IR cameras and reflective markers placed on the runners to estimate their pose. This is then used to estimate various spatiotemporal, kinetic and kinematic parameters with high accuracy. While motion capture systems can provide valuable information for modeling interactions in real-time, they would require runners to remain in one place typically indoors in labs with reflective markers attached to various parts of their body.

Treadmills are commonly used by runners who run indoors. Peloton Tread 14 and Zwift 15 are examples of commercial systems that interact with runners during their run. These semi-static setting allow for engaging interactions. Peloton Tread uses a screen attached to the treadmill, where professional trainers guide and motivate runners to achieve specific heart rate or maintain constant pace. The Zwift system enables runners to control a virtual character using the distance and speed measured by a foot-mounted tracker while running on a treadmill. Using Zwift, runners can compete with virtual characters worldwide and view their tracked data on an online dashboard accessible via mobile phones or computers. Systems that use treadmills and interact with runners during the run help motivate runners and reduce their rate of perceived exertion [86, 91]. Running Wheel [86, 91] and Exertainer [2] shows how exergaming and elements of competition and collaboration can further encourage people to enjoy and endure physical exercise. However, with increased competitiveness there is a risk that runners may adopt poor running forms, increasing their chances of injury and reducing performance. While these systems increase motivation and provide guided workout for learning various techniques, they may not ensure correct technique implementation or track essential gait parameters that prevent injuries and improve performance. Systems with integrated force plates [21] can assist runners understand, identify, and improve their running technique by detecting various kinematic, kinetic, and spatiotemporal parameters. However, these systems often lack engagement enhancing elements or guidance on improving running technique.

Robots have also been employed to support and enhance running activities. Puma’s BeatBot 16 is a commercial robot designed to assist runners in improving their pace performance on a running track. By providing real-time feedback on the pace they need to beat/maintain, through its movement on the track, the BeatBot helps runners visually track their progress and strive for better results. Similarly, the research work of Mueller and Muihead [82] explored the use of drones, flying robots, to aid runners maintain their desired pace. Additionally, studies by Ishmael et al. [55], Kim et al. [63], Witte et al. [132] have investigated robotic exoskeletons to aid runners in real-time gait adjustment and overall running technique improvement, making adjustments to various lower body:

\[\text{www.qualisys.com/analysis/running/} \]
\[\text{www.onepeloton.com/tread} \]
\[\text{www.zwift.com/eu/run} \]
\[\text{www.puma-catchup.com/puma-introduces-the-beatbot} \]
joints. However, there are limitations with robotic technology like the BeatBot, which relies on paved tracks, restricting runners to specific locations. Drone systems, while versatile, still face hardware, flight time, and legal limitations. Robotic exoskeletons, while beneficial for performance enhancement and injury prevention, can hinder running freedom due to their weight and bulkiness, as well as confine runners to specific locations [55, 132].

4 POSITIONING RUNNING INTERACTION TECHNOLOGIES TO THE FORM OF INTERACTION DIMENSIONS

We categorized the discussed works to gain new insights into the possibilities of creating more effectively utilized sports interaction technology. Our categorization process was based on dimensions derived from the Sports ITECH framework [97]. We incorporated four categories explicitly defined in the form branch of the framework (Space, Time, Feedback Modality, and Nature of Exercise Modification) and introduced two additional categories derived from the text mentioned in the function branch of the framework: “Sensing” (covering on-body or off-body sensors) and “Running Parameters” (encompassing spatiotemporal, kinetic, kinematic, and physiological parameters specifically relevant to running).

Using this approach, we created a table (Table 1) that organizes the identified works into groups based on the core technology or combination of technologies driving the interaction. Below, we have provided definitions for each category, using some of the identified works as examples to enhance the clarity of these definitions. These categories help answer questions related to Where, When, How, and What, following the Design Space Analysis method introduced by MacLean et al. [74] and implemented by Lakier et al. [70].

**Space:** The category of space relates to ‘where’ the interaction with the technology takes place, concerning the location of the running activity. In-situ systems such as the Wavelight [129], Pace-Guard [33], Keep the Beat [12], and BeatBot [99] are used within the location of regular running practice to help train the pace/cadence of runners. Ex-situ systems such as VRUN [137] and Zwift [141] are used outside the location of regular practice to help runners reach the necessary exertion levels using game-like elements.

**Time:** The category of time relates to ‘when’ the interaction takes place concerning the running activity. Prospective systems like activity Bands/smartwatches and smartphone applications allow runners to interact with the system before the start of the running practice by letting them view their past running data or help set targets before the start of their run. Conceptive systems like FootStriker [45], Strive [124], and Run, Bep, Breathe [126] interact with the runner by helping runners correct their foot strike using haptics [45] and regulate breathing using haptics [124] or audio [126] during the run. Retrospective systems like on-body trackers and smart insoles/socks interact with the runner by communicating spatiotemporal, kinetic, and kinematic parameter information after the completion of the running practice.

**Feedback->Modality:** The category of modality relates to ‘how’ the information is communicated to the runner. Visual Systems like Keep the Beat [12] and Zombies, Run! [120] use various forms of audio to interact with runners during their run. Haptic systems like RunningCoach, FootStriker, and Strive use various properties of haptics to help runner perceive their cadence [5], foot strike [45], or breathing pattern [124] using tactile actuation or kinesthetics.

**Nature->Exercise Modification:** The category of exercise modification relates to ‘how’ the communicated information modifies the running activity. The interactions of informing systems like activity band/smartwatches, on-body trackers, and #WaveLight [129] do not alter the running practice but provide athletes additional information about their running form relating to spatiotemporal, kinetic and kinematic parameters. The interactions of augmenting systems like RunRight [92] and Zombies, Run! [120] enhance the running practice while keeping it grounded to the original practice through engaging visual & audio messages to work on posture & stride rhythm during the run and story based feedback that help train pace, respectively. The interactions of transforming system like VRUN [137] use game-like elements to transform running practice while giving rise to a different exercise that involves running but not in the traditional sense.

**Sensing:** This category relates to ‘how’ the sensing of movements take place during the run. While not a category under the form branch, the function-application scope branch includes discussions on how the various technology senses relevant data. Systems like Activity Bands/Smart Watches [31, 36, 96, 130], on-body trackers [35, 81, 104, 116], and FootStriker [45] use sensors that are placed on the body to sense running movements that enable interactions. Systems like Zwift, Running Wheel [86, 91], and Force Plate Treadmills [21] use sensors that are placed outside the body to sense movements that enable interactions. On the other hand, systems like the BeatBot [99] and the drone used by Mueller and Muirhead [82] interact without relying on sensing any real-time information. These systems provide feedback on pace using programmed values.

**Targeted Running Parameters:** This category relates to ‘what’ kind of running information is targeted. In the technical domain section of the function-sports training branch, identified as key performance indicators, their relevance and selecting relevant parameters in facilitating meaningful interactions is briefly discussed. Spatiotemporal parameters concern spatial (distance) and temporal (time) parameters related to the gait of running. Some examples of these parameters include stride & step length & time, stride speed, cadence, average speed, and total distance. Kinematic parameters describe the motion of joints/segments of the running body, using the factors like angular/linear positions, velocity, and acceleration. Kinetic parameters describe the various forces, moment, and torque acting on the joints/segments of the running body. Some examples of these parameters include ground reaction forces, loading rates, braking force, and pressure distribution. Physiological parameters relevant to running include elements of cardiovascular and respiratory systems. Some of these include heart rate, SpO2 levels, blood pressure, and respiration rate.

Our analysis of the existing works using the framework in Table 1 has unveiled several opportunities for enhancing the running experience through innovative approaches. However, it’s important to recognize that our findings come with a few caveats. Firstly, the scope of running interaction technology is vast, and it is possible...
that we may have overlooked some works that could challenge the identified opportunities. Secondly, we acknowledge that the methodology we employed to categorize the various works is not the sole approach and alternative perspectives may exist. Moreover, the relevance and categorization of different forms of interaction may evolve over time as technologies advance and integrate into the running context.

When we take a broader view of the framework, we can discern opportunities for maximizing the potential of existing technologies to better support the well-being of runners. By combining technologies such as on-body trackers, smart insoles with smartphone or smartwatch applications, audio systems, and LED lights/screens, there is potential to provide meaningful feedback targeting spatiotemporal, kinetic, and kinematic parameters that directly impact injury prevention and performance improvement. Moreover, the feedback need not only inform runners but also augment or even transform their running experience. With the various combinations of available technologies, the specific parameters that can be targeted, and the potential to shape the running activity, there are numerous opportunities that merit further investigation.

Upon closer inspection, we observed that only a few interactive systems use kinetic or kinematic parameters for real-time running interactions. Regarding spatiotemporal parameters, real-time interactive systems focus on pace, distance, and speed. Obtaining kinetic and kinematic data often requires the use of on-body sensors, force

Table 1: Categorization of Running Interaction Technology using Form of Interaction Dimensions

<table>
<thead>
<tr>
<th>Technology</th>
<th>Works</th>
<th>Space</th>
<th>Time</th>
<th>Feedback Modality</th>
<th>Nature</th>
<th>Exercise Modality</th>
<th>Sensing</th>
<th>Target Running Parameters</th>
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<tbody>
<tr>
<td>Activity Band/Smart Watches</td>
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Note: A stroke fill indicates that the specific work targets only a limited set of running parameters.
sensors, or reflective markers, which can be burdensome or restrict the runner to specific spaces. Furthermore, existing work show that these systems typically provide post-run feedback with limited emphasis on real-time feedback. The work by Hooren et al. [50] emphasizes the advantages of providing runners with real-time feedback on their kinetic, kinematic, and spatiotemporal parameters as such information could assist runners in improving their running form and reducing the risk of injury. Similarly, Amini et al. [3] emphasize runners’ preference for real-time feedback. Real-time interactions would enable runners to make on-the-go adjustments, leading to improved running performance. Therefore, a gap exists for systems capable of providing real-time feedback to facilitate better movement while unencumbering runners and sensing relevant movement data. We believe that a drone holds a lot of potential to bridge this gap, leading to the emergence of a niche field we define as “runner-drone interaction.” Drawing inspiration from the established field of human-drone interaction, this niche field presents exciting possibilities and untapped opportunities for the integration of drones into the running context. In the following section, we provide further insights by exploring examples from existing research in the field of human-drone interaction and highlighting drone’s potential application in the context of running.

5 UTILIZING DRONES TO SUPPORT RUNNING WELL-BEING

Drones are versatile flying robotic systems that can be equipped with a wide range of sensors and actuators, capable of navigating diverse terrains to facilitate various interactions. Interestingly, among the identified technologies, drones remain relatively underutilized and have not received extensive research attention in the field of running. This presents an unique and underexplored area of research within the realm of running interaction technology (RIT). Unlike the technologies that require runners to wear or carry them on their bodies, drones are robotic systems that runners do not need to wear or carry. Furthermore, in contrast to ground-based robots, drones offer a higher degree of motion. As robotic systems, drones can incorporate a variety of passive sensors and actuators that can be leveraged to support interactions. By allowing runners to move unencumbered, drones open up new research avenues for designing both the drones and drone-based interactions aimed at enhancing various aspects of running, as we explore further below.

Nowadays, commercial drones equipped with cameras are common and can capture real-time or recorded aerial videos from various angles of a run. Traditionally, sports scientists have used video analysis software to obtain kinetic, kinematic, and spatiotemporal running parameters without obstructing the runner’s movements, thus enabling post-hoc analysis. Previous studies, such as those by Dingener et al. [27] and Lafferty et al. [69], used software like Kinovea [17] or Hudl [18] to manually or semi-automatically estimate runners’ 2D joint positions. However, advancements in artificial intelligence (AI) have facilitated automatic and real-time estimation of these 2D joint positions [DeepCut [53], DeepLabCut [76], DeepPose [121], AlphaPose [29], OpenPose [17], OpenCap [123]]. Leveraging these advancements, researchers can calculate spatiotemporal, kinematic, and even kinetic running parameters, enabling the detection of changes in gait patterns across specific planes of motion [62, 65, 85, 112]. Zhou et al. [138] have demonstrated the potential of using drone videos for the same purpose. By combining AI advancements with drone technologies [32, 80, 90], the possibility arises to estimate runners’ movements using videos and provide feedback on their running in real-time and post-hoc. This promising avenue merits further exploration. While earlier studies lay a solid foundation for this investigation, further research is needed to compare running parameters estimated using drone cameras against conventional methods and evaluate the effectiveness of real-time estimations. Such research can shed light on how drone-based interactions can enhance runners’ physical well-being.

Graether and Mueller [40] were among the initial researchers to present the possibility of using drones to accompany runners, highlighting the potential of drone motions to communicate with runners. Building on this work, Mueller and Muirhead [82] expanded on the dimensions for designing drones that accompany runners. Although their work demonstrates that simple drone motions can impact runners’ actions, incorporating other technologies and creating modified drones [93, 127] could open up even more intriguing avenues of research. Mayer et al. [78] and Romanowski et al. [103] presented scenarios illustrating how drones, combined with cameras, speakers, or laser pointers, could support runners. Romanowski et al. [103] even conducted a limited study that demonstrated how camera drones can be used to cheer marathon runners. Given these various possibilities and existing work within the field of runner-drone interaction, researchers should strive to leverage this wealth of information to better meet the diverse functions that runners would expect drones to perform [25, 82, 93, 110].

While the full potential of drones in meeting the diverse needs of runners is still being explored [11, 46, 49, 110], existing work in the field of HDI and sports HDI offers substantial evidence of drones’ capabilities in supporting various forms of running interactions. While most existing research focused on the outdoor use of drones, which is a natural setting for running activities (in-situ) [49, 56, 82, 83, 100, 107] there are also examples of drones being utilized indoors to enhance other physical activities like boxing [140] and Tai Chi [23], demonstrating the use of drones in an ex-situ running setting and its ability to adapt to diverse running environments. Works conducted by [8, 14, 23, 82, 140] offer valuable insights into how drones can facilitate real-time interactions (conspective interactions). Earlier studies also underscore the role of drone video recordings in enabling prospective planning of sports activities [56, 71, 139], retrospective reflection on performance [102, 119], and providing a broader perspective through video analysis [102, 138]. Drones have been employed to provide feedback through various modalities, including lights [39], screens [39, 47, 136], drone movement [19, 34], projections [18, 67, 105], speakers [122], drone noise [10], and haptics [67, 111, 131, 140]. Real-time visual or audio cues and post-hoc video analysis demonstrate how drones can be utilized to inform users [10, 67], augment their running [82] & Tai Chi [23] experiences, and even transform running activities [46] and ball training [88, 89]. Though cameras on a

17https://www.kinovea.org/
18https://www.hudl.com/en_gb/
6 DISCUSSION AND CONCLUSION

Our aim throughout this review was to inspire researchers, practitioners, and designers to push the boundaries of running interaction technology. By highlighting underutilized opportunities and the forms of interaction available, we hope to expedite future research and practical advancements. Our aim is to witness the development of comprehensive studies that investigate various combinations of interaction forms to support runners’ well-being and performance of runners.

While we have made every effort to cover a wide corpus of work related to technology supporting running activities by utilizing running-related data, we recognize that the field is vast, and some works may have inadvertently escaped our attention. In retrospect, we recognize that additional search terms such as “jogging,” “data-driven,” “bio-feedback,” “sports performance,” “artificial intelligence,” and “support” might have unveiled additional pertinent works. Nevertheless, our compilation serves as a foundational overview of commonly encountered works and provides an entry point for future researchers looking to explore further in this specific domain. However, we must also acknowledge certain limitations in our framework. Categorizing works based on core technologies or combinations of technologies occasionally led to overlaps between technology sets. However, we focused our categorization on the core technology emphasized or driving the interaction. It should be noted that there may be additional dimensions, such as function or design dimensions, along which the works could be positioned. As interactions continue to evolve with advancing technologies, future researchers are encouraged to explore uncovering these dimensions and look into positioning relevant works along these dimensions to understand unmet opportunities.

Our exploration into running interaction technology and its convergence with runner-drone interaction has illuminated numerous opportunities within this field. By placing a spotlight on the potential of drones as a relatively underutilized technology for supporting running activities, we lay the foundation for further exploration in the domain of runner-drone interaction. While our primary focus revolves around designing interactive settings to help runners enhance their technique during regular outdoor runs, there exists ample room for research tailored to specific types of running. Specialized investigations into the design considerations for runners practicing various forms of the sport could further enrich our understanding. Moreover, the research and development of drones to support running extend beyond the realm of athletics. It contributes to the broader advancement of drone technology, with potential applications across various domains. Through our identification and emphasis on various forms of interaction categories, we aim to highlight the expansive array of opportunities available to researchers in this field. Our hope is that this encourages researchers to explore these opportunities, ultimately leading to more profound, methodologically rigorous studies focused on designing drones specifically tailored for runners.

In conclusion, this paper contributes a consolidated view of existing works in running interaction technology (RIT) and runner-drone interaction (RDI). We address unmet opportunities and provide insights into the potential growth of this field. With the increasing interest and knowledge surrounding RIT and RDI, we believe that our contribution will inspire and guide future research, leading to promising developments in the intersection of technology and running.

ACKNOWLEDGMENTS

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REFERENCES


