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Virtual Performance Augmentation in an Immersive Jump & Run Exergame

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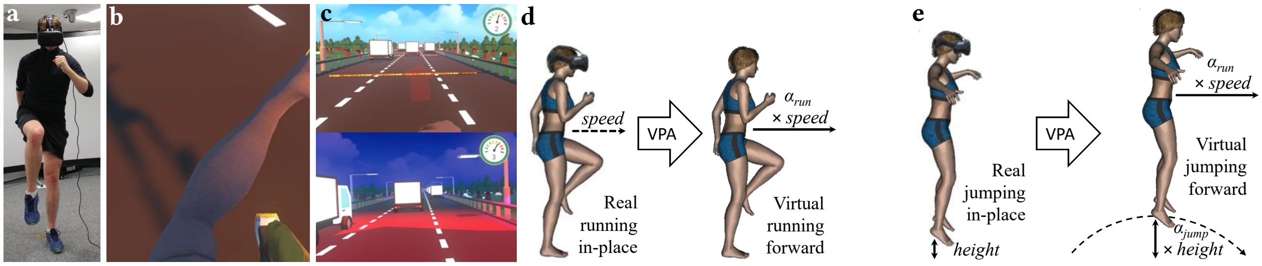

Figure 1: a) The exergame is played by running and jumping in place while wearing a head-mounted display. b) A sense of embodiment is created through visual-motor synchronicity with an avatar. c) Running, jumping over "lava gaps", and avoiding trucks during gameplay. d) In place running with estimated speed is used to simulate forward running in VR with the speed augmented by a factor α_{run}. d) In place jumping is used to simulate forward jumping in VR with the height augmented by a factor α_{jump}.

ABSTRACT

Human performance augmentation through technology has been a recurring theme in science and culture, aiming to increase human capabilities and accessibility. We investigate a related concept: virtual performance augmentation (VPA), using VR to give users the illusion of greater capabilities than they actually have. We propose a method for VPA of running and jumping, based on in place movements, and studied its effects in a VR exergame. We found that in place running and jumping in VR can be used to create a somewhat natural experience and can elicit medium to high physical exertion in an immersive and intrinsically motivating manner. We also found that virtually augmenting running and jumping can increase intrinsic motivation, perceived competence and flow, and may also increase motivation for physical activity in general. We discuss implications of VPA for safety and accessibility, with initial evidence suggesting that VPA may help users with physical impairments enjoy the benefits of exergaming.

CCS CONCEPTS

• **Applied computing** → **Computer games**; **Consumer health**; • **Human-centered computing** → **Virtual reality**.

KEYWORDS

Exergame; virtual reality; performance; running; jumping

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1 INTRODUCTION

Human performance augmentation through technology has been a theme in science and culture for decades [37]. The idea of augmenting human physical, mental and social capabilities has intrigued scientists from many disciplines [94] and led, for example, to the development of powered exoskeletons [5, 33, 131]. Similarly, performance augmentation, especially

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physical augmentation, has been a common theme in many computer games: players control characters that are more skilled, can run faster and jump higher, often far beyond a player's own realistic capabilities. Despite lack of realism, players often identify with their game character and are likely to perceive attributes of their game character in themselves [10, 46, 58, 60, 89, 115, 127]. As a result, augmentation of the character in the game becomes a *virtual performance augmentation* (VPA) of the players themselves.

Our focus here is on the use of VPA in a VR exergame, where physical performance is a central concept [86]. With immersive VR and natural interaction technology, it has become possible to map a player's real physical performance closely to the in-game performance of an avatar [28, 71, 108, 109]. This visual-motor synchronicity strengthens the identification between the player and the avatar, inducing a feeling of embodiment [59, 106] that may facilitate the creation of a convincing VPA experience. Exergames generally aim to improve the performance of the player, e.g. to improve their fitness or help them rehabilitate from a medical condition. Adding VPA to a VR exergame could have the following positive implications.

Increased Motivation: VPA may help to motivate players to engage with the exergame. It may give players a sense of empowerment by adjusting the difficulty of an exergame [15, 39], help induce a sense of flow by balancing skills and challenges [23, 74], and increase perceived competence, which is regarded as an important factor for intrinsic motivation [98, 114]. Increased intrinsic motivation is in turn linked to an increased adherence to physical exercise [2, 34, 99].

Accessibility: VPA can enable players with reduced physical capabilities to play a VR exergame that would otherwise be too difficult for them. For example, a player with a mobility impairment could be enabled to control an avatar similarly to a non-impaired player by taking individual capabilities into account [118]. Non-immersive exergames with adjustable difficulty have shown some success for players with neurological disability [76] and the rehabilitation of stroke [65]; VPA may be used to achieve similar results using immersive VR. Similarly, VPA could empower less capable players to overcome feelings of low self-efficacy [125] and enable them to compete with more capable peers. Some form of VPA is often used in game balancing methods, which adjust a player's chance of winning relative to their capabilities [8, 39].

Feedforward: VPA could be used to create an experience of an 'improved self', i.e. a self model of the player exhibiting a performance exceeding the player's current ability, in order to elicit a 'feedforward effect'. Feedforward is an established method that helps an individual improve a skill or performance by exposing them to improved self models [30, 31]. It has traditionally been applied by creating videos of an individual showing an improved behaviour [29], and more recently with interactive self models to improve performance in a VR exergame [7]. Similarly, VPA may induce a Proteus effect, i.e. a change in behaviour that conforms with a player's digital self-representation [124]. Positive transfer effects have been observed after embodying 'improved' avatars in VR: for example, avatars with 'superhero' abilities motivated consistent pro-social behaviour [95, 127], 'creative' avatars increased creativity [41], and avatars perceived as more appropriate for a musical task led to increased musical performance [57]. Embodiment of a physically higher performing avatar may induce players to adopt more active behaviours.

Scope: We propose a method for VPA of running and jumping, based on in place movements, and describe empirical results on its effects in a VR exergame. Players walk, run or jump in place according to their abilities while wearing a VR head-mounted display (HMD) (Fig. 1a). Body movements are tracked and a sense of embodiment is created through visual-motor synchronicity (Fig. 1b). Walking, running and jumping activities are recognised with a novel algorithm, based on a biomechanical analysis of human locomotion, and used as input for a jump & run exergame (Fig. 1c). We propose a VPA algorithm that processes the recognised in place activities in real-time to simulate corresponding 'natural' locomotory gaits of a given augmented performance in VR: walking, running and jumping in place are used to simulate 'natural' forward walking, running and jumping gaits, with forward speed and jump height adjusted by performance augmentation factors α_{run} and α_{jump} (Fig. 1d&e). In order to investigate VPA and its effects we pose the following research questions:

RQ1 How can running and jumping be virtually augmented using consumer-level VR?
RQ2 Are in place running and jumping suitable as physical activities in a VR exergame?
RQ3 Can VPA improve intrinsic motivation and perceived competence of the augmented activity?

VPA has previously been described using the term "mixed-reality empowerment" referring to both virtual and actual performance augmentation [43]. Players have been tracked while jumping on a trampoline [48, 55] or performing martial arts [42], showing exaggerated player movements on large screens. Player flexibility has been exaggerated using VR in a martial arts kicking task, by augmenting range of movement and kicking height [40]. VPA has also been utilised for navigation in VR by walking, allowing users to amplify their virtual speed [52] or enlarge their virtual body relative to the virtual world [62]. In addition, the effects of diminished optical flow (i.e. diminished virtual performance) have been studied for treadmill-based walking using a large screen [92].

It is generally more difficult to create a usable VPA experience in immersive VR compared to large screens as users of immersive VR are particularly susceptible to sensory conflict and VR sickness [1, 102].

Exergame researchers have identified augmentation of perceived physical performance as a largely underexplored area [44, 81]. To the best of our knowledge, there has been very little research exploring recognition and augmentation of in place running and jumping for exercise in immersive VR. The closest related work is VRun [126], a VR exergame based on running in place that does not consider augmentation. VRun identifies the accuracy of activity tracking as a major challenge; we address this by proposing a novel activity recognition algorithm based on biomechanics of locomotion. In summary, we make the following novel contributions:

(1) A method for recognition and augmentation of walking, running and jumping in VR (Section 2).
(2) Empirical evidence about the effects of virtual performance augmentation (Section 3).

2 AUGMENTING WALKING, RUNNING AND JUMPING IN VR

We first address RQ1, motivating why we use walking, running and jumping in place and describing how these activities can be recognised and augmented in a VR exergame.

Motivation: We consider game mechanics for walking, running and jumping in place to allow users to exercise at different levels of intensity and to offer a variety of biomechanical stimuli. Walking was chosen because it is the main gait of human locomotion, fairly accessible and an essential activity of daily living [47]. It has well documented public health benefits [66] and is likely important for maintaining mobility and recovering from mobility disabilities [35, 105]. Running is the most popular type of cardiovascular exercise after walking, and more natural and economical for exertion at high intensity [27, 80]. Jumping offers a biomechanical stimulus with a greater magnitude than running and a distinct pattern of body acceleration [9]. Many people with mobility impairments have difficulties running and jumping; for accessibility an exergame can be played using only slow walking motions, and jumping obstacles can be removed or ignored.

Are walking, running and jumping suitable mechanics for an exergame when they are performed in place? Walking in place (WIP) methods [12, 14, 32, 63, 82, 83, 117, 119, 121, 123] and jogging in place [67, 126] have been proposed for VR locomotion. The biomechanics of walking and running in place are similar to those of their locomotory counterparts, so it is reasonable to expect similar physiological effects. The horizontal (i.e. forward) force is greatly reduced, but the dominant pattern of vertical force is similar, with peak vertical forces 4-6 times greater than peak horizontal forces during normal locomotion [22]. Running and jumping in place are popular exercises in high intensity interval training [87] and plyometrics [24]. Running in place was touted as an effective method for improving running technique more than a century ago [38] and rediscovered more recently [78]. It was found to cause exertion similar to the common treadmill-based Bruce Protocol maximal exercise test [88]. It can be performed fairly easily and has documented health benefits [19], also for injury rehabilitation [104]. Due to reduced horizontal force, running in place may reduce shearing forces and knee strain compared to normal running [128]. People are more likely to land on the forefoot, which generates smaller collision forces compared to the more common landing on the heel and may prevent impact-related injuries [69].

Would using a treadmill be more suitable than exercising in place? Running on a treadmill facilitates a more natural gait including horizontal force. However, there are limitations with this setup. Walking on a treadmill poses safety challenges, which are typically mitigated by use of handlebars or a harness [36, 92, 107]. Running exacerbates these challenges and renders simple solutions such as handlebars infeasible, while jumping on a treadmill is very dangerous even without wearing a HMD [56]. Treadmills for walking in VR are bespoke systems that are not typically available to consumers; they limit a player's range of motion making vigorous exercise difficult, can take up considerable space, and would add markedly to the cost of an exergame setup [4, 91, 107]. Walking on a treadmill in VR can reduce VR sickness [53]; however, it leads to distortions in the perception of movement [90] and different gait characteristics compared to walking in the real world [93].

System Overview: We propose a system for walking, running and jumping in VR based on consumer hardware such as a HTC Vive HMD and a Kinect 2 depth camera for body tracking. Knee and foot positions are tracked by the Kinect at 30 Hz, while the HTC Vive is used to track the head position and orientation at a minimum of 50 Hz. The bipedal gait cycle is well understood, therefore we base our algorithm for recognition of walking, running and jumping on a biomechanical and kinematic analysis of human gait.

Per-User Calibration

In order to adapt the system to a user's physical capabilities, we record characteristic features of a user's activities in a calibration phase. To determine ground level, we track the vertical position of the user's feet while standing and calculate an average value *groundY* over three seconds and both feet. Then we ask the user to run in place for 10 seconds, starting slowly and building up to a run of maximum intensity so that the full kinematic range is represented. We record:

average $avgHeadY_{run}$ vertical head position $headY$; minimum $minHeadV_{run}$, average $avgHeadV_{run}$ and maximum $maxHeadV_{run}$ absolute vertical velocity of the head $headV$; minimum $minKneeV_{run}$ and maximum $maxKneeV_{run}$ absolute vertical velocity of the knees relative to the hip $kneeV$ (average of both knees), and minimum $minCadence$ and maximum $maxCadence$ cadence.

Cadence in steps per minute is estimated based on a function *feetGrounded*, which detects how many feet are currently touching the floor: a foot is considered grounded if $footY \leq groundY + \epsilon$, with ϵ chosen to accommodate for errors in the tracked vertical position of the feet. During walking, *feetGrounded* alternates between two and one; during running, it alternates between zero and one (Figure 3). Similar to Wendt et al. [117], we consider the phases of the gait cycle in order to improve the time-resolution of the cadence estimate: we measure the half-stride time t_{step} (the time between steps in seconds) starting either at collision (increase of *feetGrounded*) or toe-off (decrease of *feetGrounded*), whatever occurred most recently. If the last change of *feetGrounded* was an increase, we calculate t_{step} as the time to this increase from the increase before, and analogously for decreases. Based on this, we calculate cadence considering the time Δt that has passed since t_{step} was last updated by a collision or toe-off, so that cadence drops immediately as the time between steps increases:

$$cadence = \begin{cases} 60/t_{step} & \text{for } \Delta t \leq t_{step} \\ 60/\Delta t & \text{for } \Delta t > t_{step} \end{cases}$$

Lastly, we ask the user to repeatedly jump in place for 10 seconds, recording $minHeadY_{jump}$, $maxHeadY_{jump}$ and $avgHeadV_{jump}$ similar to running. In order to estimate an $avgHeadV_{jump}$ characteristic of the push-off and landing phases of a jump, where the velocity is markedly higher than for running, we consider values of *headV* only when $headV > avgHeadV_{run}$. We also record the minimum value $minKneeA_{jump}$ and average $avgKneeA_{jump}$ of the angles at the knee joints $kneeA$ (average of both knees), and the minimum $minKneeD_{jump}$ and maximum $maxKneeD_{jump}$ vertical distances of the knees from the hip $kneeD$ (average of both knees). $kneeD = 0$ means the knees are level with the hip; $kneeD < 0$ means the knees are below the hip. $maxKneeD_{jump}$, $minKneeA_{jump}$ and $minHeadY_{jump}$ are typically reached at the end of the counter-movement phase or during the landing phase, when users bend their knees to prepare for or recover from a jump; $minKneeD_{jump}$ and $maxHeadY_{jump}$ are typically reached in the aerial phase [70].

Taking the average of values measured in each leg for the calculation of $kneeV$, $kneeA$ and $kneeD$ improves accuracy and amplifies distinguishing characteristics of running, walking and jumping. During walking, only one knee is moving at a time (Fig. 3), leading to a $kneeV$ lower than that of the moving knee. By contrast, during running both knees are moving simultaneously with similar absolute velocity in opposite directions, leading to a $kneeV$ that is markedly higher than for walking and likely more accurate than the measurement of a single knee alone. As mentioned, $kneeA$ and $kneeD$ typically reach their extrema during jumping; both knees are similarly bent making averages more accurate in this case. By contrast, running and walking are asymmetrical movements, reducing $kneeA$ and $kneeD$ compared to individual measurements of each leg and making the difference to the symmetrical movements of jumping more pronounced.

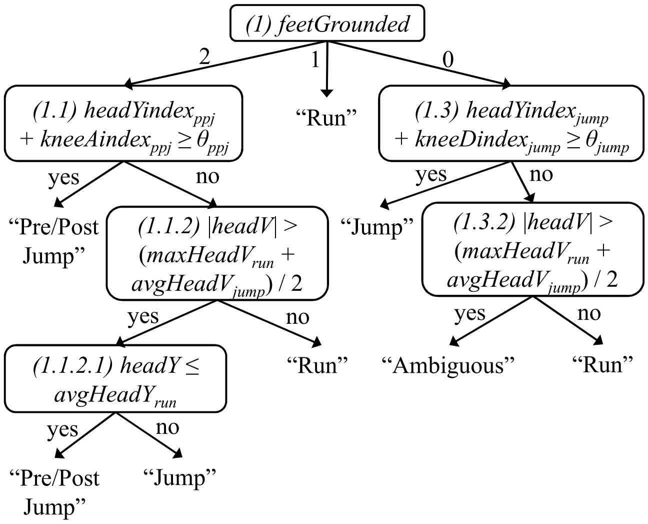

Figure 2: Decision tree for the classification of locomotion activities.

Activity Recognition

Our algorithm is a classification tree (a.k.a. decision tree) [13], illustrated in Fig. 2, which is applied for every rendered frame of the game based on the following tracked input variables: *feetGrounded*, $headY$, $headV$, $kneeV$, $kneeA$ and $kneeD$ (Fig. 3). All input variables relate to features of the head and legs in order to include users with impaired mobility in the upper limbs. The algorithm recognises the following classes: 'Run', 'Jump', 'Pre/Post Jump', and 'Ambiguous'. Class 'Run' abstracts from the speed of locomotion and encompasses not just running in place, but also walking in place and standing on the spot. These activities are distinguished by their estimated forward velocity as described in the next section. By classifying walking as 'Run,' users with physical impairments can run virtually through VPA by walking in place. 'Pre/Post Jump' encompasses the counter-movement, early push-off and late landing phases of a squat-jump movement

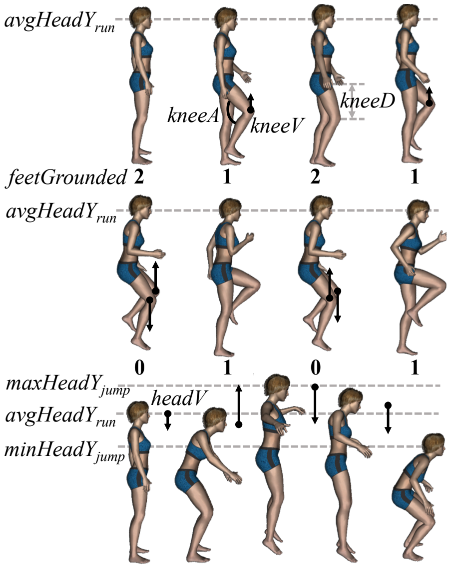

Figure 3: Walking, running and jumping in place (top to bottom).

[130]; by recognising it, the forward momentum of real jumping while running can be simulated when squat-jumping in place. The late push-off, aerial and early landing phases, in which a user is committed to jumping, are classified as 'Jump'. The 'Ambiguous' class signifies transitions between jumping and running, which are resolved naturally as the activities progress. In the following we refer to the decision node numbers in Fig. 2.

The root node (1) is defined on function *feetGrounded*. If only one foot is grounded, this is characteristic of running and classified as 'Run'. It may also happen for asymmetrical push-off or landing during a jump, but this is quickly resolved as the second foot leaves or hits the ground, with 'Run' ensuring that smooth forward momentum is simulated. In case both feet are grounded (1.1), we try to distinguish the squat-like movements of 'Pre/Post Jump' (i.e. counter-movement, early push-off and late landing) from running by calculating an index representing the similarity of $headY$ to the relevant calibration parameters $minHeadY_{jump}$ and $avgHeadY_{run}$:

$$headYindex_{ppj} = \frac{avgHeadY_{run} - headY}{avgHeadY_{run} - minHeadY_{jump}}$$

Using this inverse linear interpolation, this index is 0 if the current head height is the average for running and 1 if it is the lowest observed during pre/post jumping phases.

With a similar intention and further differentiation of 'Pre/Post Jump' from 'Jump', we calculate an index representing the similarity of $kneeA$ to the calibration parameters $minKneeA_{jump}$ and $avgKneeA_{jump}$:

$$kneeAindex_{ppj} = \frac{avgKneeA_{jump} - kneeA}{avgKneeA_{jump} - minKneeA_{jump}}$$

This index is 0 if knee bend is average, signifying the relevant transitions to late push-off or from early landing, and 1 if it is at the minimum observed during pre/post jumping phases, i.e. at the end of the counter-movement or just before the landing recovery phase. The two indices are considered in combination $headYindex_{ppj} + kneeAindex_{ppj}$ and compared to a threshold θ_{ppj} to differentiate 'Pre/Post Jump' from 'Run' and 'Jump'. For our experiments we chose $\theta_{ppj} = 1$, which we determined empirically in pilot tests. A similar concept is used in node (1.3). The other nodes compare the tracked variables directly with the characteristic features recorded in the calibration phase.

Run Augmentation

In order to achieve a realistic experience, the way players control their virtual movements varies based on the recognised locomotion class. During 'Run', in place and lateral movements are applied directly based on head tracking, whereas forward velocity *speed* can merely be estimated based on the tracked kinemetric variables. We address requirements similar to WIP such as low latency, smoothness and continuous control of estimated locomotion speed [14, 32, 117]. The 'Run' locomotion class includes WIP as well as running in place, therefore this estimation must accommodate the differences between the two gaits [22, 67, 73, 80]. We use a new, integrated approach to estimate both walking and running speed based on biomechanical considerations, related work on WIP [12, 14, 32, 63, 67, 82, 83, 111, 113, 117, 119–121, 123] and empirical experimentation.

Cadence is known to be correlated with walking speed [25, 50, 51] and is an important factor (sometimes the only factor) in many WIP approaches [12, 63, 83, 117, 119, 121]. Head velocity has been found to be a good indicator of cadence [113]; it is more continuous in nature than a step count and has been used exclusively for WIP [111] as well as jogging in place [67]. Knee velocity correlates with cadence and forward velocity [50, 51], as well as leg lift and foot velocity, both of which have been used as exclusive factors for WIP [14, 32, 120, 123]. Hip flexion and hence knee displacement relative to the body correlate with running speed [75]; sprinters lift their knees higher than long distance runners. This is also reflected in a higher footstep amplitude, which has successfully been used for WIP [14].

The variables *cadence*, *headV*, *kneeV* and *kneeD* correlate with running speed. To account for a player's individual physical capabilities, we normalise them according to the range of values exhibited during the running calibration phase, by linearly transforming $[minimum, maximum]$ to $[0, 1]$. The variables correlate positively with speed, therefore we estimate speed linearly as a weighted sum:

$$
\begin{aligned}
speed' = speed_{aug}\Bigg(& w_1 \frac{cadence - minCadence}{maxCadence - minCadence} \\
& + w_2 \frac{kneeV - minKneeV_{run}}{maxKneeV_{run} - minKneeV_{run}} \\
& + w_3 \frac{kneeD - minKneeD_{run}}{maxKneeD_{run} - minKneeD_{run}} \\
& + w_4 \frac{headV - minHeadV_{run}}{maxHeadV_{run} - minHeadV_{run}} \Bigg)
\end{aligned}
$$

$$
speed = \begin{cases} speed' & \text{for } kneeV \geq minKneeV_{run} \\ 0 & \text{otherwise} \end{cases}
$$

The formula cannot easily be ‘cheated’, e.g. by bobbing only the head, as the linear combination $speed'$ is applied in the final estimate *speed* only if the knees are moving and the player’s movements have already been classified as ‘Run’. $speed_{aug}$ is the augmented performance (speed in km/h) produced by the algorithm, i.e. the approximate running speed perceived by the player during typical gameplay. We call this *absolute VPA* as the performance is augmented irrespective of a player’s real performance such as their typical running speed $speed_{real}$. It is more realistic to augment performance relative to a player’s real capabilities – *relative VPA* – and this can be achieved by using an augmentation factor $\alpha_{run} = speed_{aug}/speed_{real}$ (Fig. 1d).

We chose weights $w_1 = 0.07$, $w_2 = 0.48$, $w_3 = 0.48$ and $w_4 = 0.24$ based on biomechanical considerations (see below) and empirical tests. First, weights were estimated and adjusted in pilot tests. Then the game was tested with players (6 female, 9 male) of various running abilities with estimated average speeds over 5 km ranging from 8 to 17 km/h. For each participant we manually scaled the weights based on feedback, so that the participant’s game experience approximately matched their experience of real-world running at their estimated real speed. Optical flows in VR are notoriously hard to match with real-world locomotive optical flows, with most users underestimating their speed in VR [83]. We mitigated this by making participants aware of this bias and showing them real-world first-person videos illustrating estimated running speeds before running in VR, giving them a ground truth to compare to. In order to calculate the final weights, a simple linear regression was performed to predict the scale of the weights based on estimated real running speed, without constant as all weights must be zero to guarantee an augmented speed of zero. A significant regression equation was found (F(1, 14)=251.2, $p < .001$), with $R^2 = .95$. This resulted in weights that approximate a real running experience for a given $speed_{aug}$.

In contrast to many WIP approaches, our weight for *cadence* is low because of differences between gaits and considerations of accuracy. For walking, forward velocity is equal to cadence times stride length [129], and the latter can be estimated from cadence and body height [25, 51]. By contrast, for running, anthropometric variables such as height or leg length cannot be used to predict stride length accurately; the latter varies based on running speed [18]. For walking, cadence and stride length are strongly positively correlated [51, 100]. By contrast, many runners hold their cadence fairly constant irrespective of their speed [116]. As a result, the linear relationship of cadence to speed is weaker in running compared to walking. Also for WIP, the accuracy of cadence as a sole predictor of speed has been criticised because of the differences between stepping in place and actual walking [14, 82] – during WIP steps can be performed more quickly due to the absence of forward velocity. Furthermore, cadence measurements suffer from latency and discontinuity as cadence may change between steps, potentially leading to a delayed and abrupt change in speed [14, 32, 117]. As a result, VPA of running could not be implemented well using only sensor mats, which measure mainly cadence. In order to provide a smooth running experience, other variables such as knee velocity and displacement need to be considered.

Relative knee velocity (*kneeV*) contributes strongly to forward velocity, as power is largely generated by extension of the hip, which accelerates the knee downward, while the other knee is accelerated upward by hip flexion [50, 51]. Changes in *kneeV*, which are reflected in changes of forward velocity, can be accurately measured with low latency. The power generated by the hip is also strongly reflected in the degree of hip flexion and hence knee displacement *kneeD* relative to the body [14, 75]. As a result, both *kneeV* and *kneeD* are strong indicators of forward velocity and are weighted highly. Movements of the legs cause corresponding movements of the head, and the latter can be measured with higher temporal resolution and accuracy by the HMD compared to the Kinect. Other WIP researchers found tracking data from a single Kinect to be too noisy for robust WIP [121], and this can be mitigated by integrating measurements from other sensors such as the HMD. Head velocity correlates with cadence but can be measured more accurately and continuously [113]. Although movements of the head are only indirectly related to walking/running speed, they have previously been found useful in estimating speed of jogging in place [67]. We found they assisted in creating a smooth and natural running experience, hence assigning *headV* a medium weight.

Jump Augmentation

During jumping, in place and lateral movements are again applied directly based on head tracking. During ‘Pre/Post

Jump', the speed of the player estimated from immediately preceding walking/running is preserved in order to create a smooth experience of the player's momentum carrying forward. During 'Jump', the aerial phase is augmented along both the vertical and forward axes (Fig. 1e): the vertical distance of the player from the ground is scaled proportionally according to α_{jump}, while the augmented running speed estimated immediately before the jump is preserved [45, 72, 101]. As a result, the avatar jumps higher but not longer than the user and lands on the ground at the same time as the user, in order to prevent sensory disconnect and loss of balance.

Evaluation of Augmented Running & Jumping

We evaluated the proposed VPA method by testing how well it is able to deliver an acceptable experience of running and jumping in VR across different levels of performance augmentation. We chose evaluation criteria that have previously been used to evaluate the quality of WIP [14, 82, 83, 121]: naturalness, realism and responsiveness.

We used a between-participants design, varying the augmented speed of running $speed_{aug}$ and the augmentation factor for jumping α_{jump} together, from a 'realistic' performance of $speed_{aug} = 9$ km/h and $\alpha_{jump} = 1$ up to an extremely exaggerated performance of $speed_{aug} = 88$ km/h and $\alpha_{jump} = 25$ (see x-axes in Fig. 4). Jumping was augmented more strongly in proportion to running as we found jumping augmentations were less noticeable. The between-participants design was chosen in order to avoid fatigue, as the game was tiring and participants would otherwise have had to play many rounds.

We recruited 80 participants (22 female, 58 male, average age 23, 62 reporting previous experience with VR) from the campus of the University of Bath and randomly assigned each to one of six augmentation groups. First we demonstrated the system to each participant and guided them through the calibration process. Then the participant had time to freely play the exergame for several minutes by running and jumping at the assigned level of augmentation. Finally, we asked the participant to complete a questionnaire about their experience, consistent with those used by other researchers to evaluate WIP and immersive experiences [6, 14, 64, 68, 82]. Single 7-point Likert-scale items were used to measure perceived Naturalness, Consistency with real-world experiences, and perceived Responsiveness of running and jumping, respectively; the Naturalness (NATRL) subscale of Witmer & Singer's Presence Questionnaire (PQ) [122] and open feedback were used to evaluate the overall experience. The procedure took about 5-10 minutes.

We hypothesised a priori that quality scores would be at least above scale-midpoint, i.e. at least 'moderately' natural, consistent and responsive based on the descriptive label in the PQ – a criterion consistent with results from studies of WIP and VR [64, 68, 82]. Based on a power analysis, the study was able to detect 'large' effects between augmentation levels (Cohen's f≥0.42), 'medium' sized effects between the quality of running and jumping (Cohen's f≥0.18), and 'medium' sized interaction effects (Cohen's f≥0.18) at significance level $\alpha = 0.05$ with a power of 0.8. This allows us to to better understand uncertainty in the results.

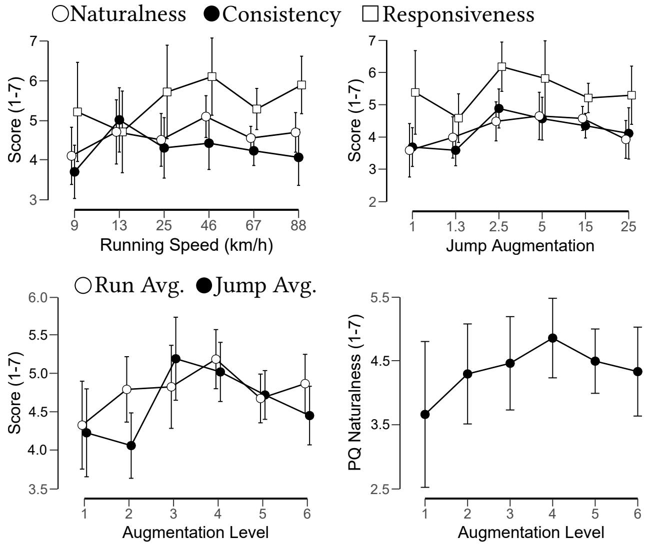

Figure 4: Naturalness, Consistency and Responsiveness scores (1-7, higher is better) for Running (top-left) and jumping (top-right), average quality scores for running and jumping (bottom-left) and overall PQ Naturalness scores (bottom-right) across different augmentation factors.

Results. The variances in each group were similar enough and the measurements' distributions close enough to normal, with sufficient sphericity, to warrant analyses of variance (ANOVA). The level of significance used was $\alpha = 0.05$. All graphs show 95% confidence intervals of the mean. Two-way repeated measures ANOVAs were conducted on the effects of Augmentation Level (1-6) and Activity (Running and Jumping) on Naturalness, Consistency and Responsiveness (Fig. 4 top). The main effect of Activity on Naturalness was significant, $F(1, 74) = 6.57, p = .01$, indicating that Running felt significantly more natural than Jumping with a 'medium' effect size (Cohen's d=0.27). All other main effects of Augmentation Level ($F(5, 74) \leq 1.46, p \geq .22$) and Activity ($F(1, 74) \leq= 0.17, p \geq .68$), and all interaction effects ($F(5, 74) \leq 2.09, p \geq .08$) were not significant. Directed one-sample t-tests of the marginal means showed that Naturalness and Responsiveness scores for Running, Responsiveness scores for Jumping, and the averages of Naturalness, Consistency and Responsiveness scores for Running and Jumping (Fig. 4 bottom-left) were all significantly greater than the scale mid-point 4, $t(79) \geq 4.02, p < .001$, with at least 'medium' effect sizes (Cohen's d≥0.45). Consistency of Running ($t(79) = 1.58, p = .06$) and Jumping ($t(79) = 1.27, p = .10$), and Naturalness of Jumping ($t(79) = 1.51, p = .07$) were not significantly above 4. A one-way ANOVA showed that the main effect of Augmentation Level (1-6) on PQ Naturalness was not significant, $F(5, 74) = 1.16, p = .34$ (Fig. 4 bottom-right). A directed one-sample t-test of the marginal mean showed that PQ Naturalness was significantly greater than the scale mid-point 4, $t(79) = 2.88, p = .003$, with a 'medium' effect size (Cohen's d≥0.32).

Discussion. Comparing running and jumping in place with normal running and forward jumping sets a high bar as they have different kinematics and kinetics [22, 45, 84] and can never feel exactly the same. Also, real running and jumping generally cannot deliver a performance on par with augmented activities, which are therefore unlikely to feel entirely natural. All quality measures were on average above scale mid-point and most were significantly above; however, naturalness of jumping and consistency of running and jumping with real-world experiences were only close to significant. Overall the results indicate that the proposed VPA method produces experiences of at least moderate quality, roughly on par with other WIP and VR experiences [64, 68, 82], with augmented jumping feeling less consistent and natural than augmented running. In conclusion, the VPA method works sufficiently well to warrant investigation of its use in a VR exergame, but it has some limitations. We observed that if the running/jumping behaviour in the calibration phase was different from the behaviour during gameplay, then this could negatively affect recognition and augmentation quality. In particular the participants unfamiliar with VR had a tendency to move around in the room, and when they got too close to the Kinect this negatively affected tracking and augmentation quality. In this study participants only played the game for a few minutes as the exergame is based on a high-intensity interval training protocol and not intended for longer periods of use. Our observations from longer use indicate that players became fatigued and had to reduce the intensity of their movements.

3 EFFECTS OF AUGMENTATION IN A VR EXERGAME

In order to investigate the effects of VPA and answer RQs 2-3, we conducted an experiment with the degree of Augmentation and augmented Activity as independent variables (see Table 1). For Augmentation we used a within-participants design, with conditions "no augmentation" ("N", augmentation factor $\alpha = 1$), "low augmentation" ("L", $\alpha = 1.3$) and "high augmentation" ("H", $\alpha = 2$). Augmentation factors were chosen based on considerations of realism and perception. A performance increase of 30% (L) in running speed and jumping height is high but not entirely unrealistic for average individuals [3, 21]. However, users tend to overestimate their real physical speed during VR walking (treadmill and WIP) by a factor of 2 [83], so may in fact perceive L as a reduction of their real performance. A performance increase of 100% (H) is generally unrealistic, but would likely be perceived as an increase given the bias observed in VR walking. We chose L to explore subtle effects of VPA, and chose H to validate hypothesised effects when users can consciously perceive increases in their own performance. For Activity we used a between-participants design with one group for "augmented running and unaugmented jumping" (R) and the other group for "augmented running and augmented jumping" (RJ). This allowed us to explore differences caused by the augmentation of jumping, which was perceived differently from running during our evaluation of the VPA method (Section 2 above).

Outcome Variables. We measured participants' exertion based on heart rate (HR), using a Garmin 620 chest-strap monitor. Average and peak HR was expressed as a percentage of a participant's estimated maximum HR (HR Avg% and HR Peak%). Based on ACSM guidelines [85], maximum HR was estimated as 220 minus age. This measure is commonly used in exercise studies to confirm participants are working at a required level of exertion. We also used the Borg Rating of Perceived Exertion Revised Category-Ratio Scale (RPE), which has a range of 0 to 10. We measured immersiveness of VPA with the Immersive Experience Questionnaire (IEQ) [54], which has been previously used for exergames [7, 17]. We recorded IEQ scores as an average over item scores between 1 to 7, with 7 representing the most immersion. We measured intrinsic motivation of VPA with the Intrinsic Motivation Inventory (IMI) scale [96], which has been validated for sports and exercise [20, 77]. We used only the Interest/Enjoyment subscale, which is considered the main self-report measure, and the Perceived Competence subscale. IMI scores range from 1 to 7, with 7 representing the highest enjoyment or perceived competence. We also measured participants' motivation for physical activity in general using the RM 4-FM Motivation for Physical Activity questionnaire (RM 4-FM) [26, 97], which has been used in many health and exercise studies [110]. RM 4-FM produces an Autonomy Index score representing the relative impact of intrinsic and extrinsic factors in a participant's motivation to be active. Negative numbers signify dominance of extrinsic motivation in the regulation of active behaviours; positive numbers reflect dominance of intrinsic motivation, which is linked to an increased adherence to physical exercise [2, 34, 99]. We measured flow experienced during VPA using the Positive Psychology Lab's Flow State Questionnaire (FSQ) [74], which has been validated with exergames, including both subscales "Balance of Challenges and Skills" (Balance) and "Absorption in the Task" (Absorption). We recorded FSQ scores as averages over all item scores between 1 and 5, with 5 being the strongest flow.

Exergame. The VPA exergame is very similar to other VR exergames [7, 11, 103]. A straight road is shown ahead of the player, with slow moving trucks as obstacles that can be avoided by moving to the side (collisions are of no consequence). A sense of embodiment is induced through visual-motor synchronicity with an avatar and a visible ground-plane shadow of that avatar (Fig. 1b). Two alternating scenes provide variety in the gameplay (Fig. 1c top and bottom): a "daytime" scene adds "lava gap" obstacles across the road at regular intervals, which are stimuli for the player to jump over (running through them is of no consequence); in a "nighttime" scene a large VR character chases the player, casting a visible shadow on the road and serving as a stimulus for fast walking/running. The game was configured to last $5^{1}/_{2}$ minutes per play session, with 90-second warm-up and cool-down phases (both using the "daytime" scene) and two 30-second higher-intensity phases (using the "nighttime" scene) with a 90-second recovery phase ("daytime" scene) in the middle. This is similar to a protocol used in high-intensity interval training [7]; however, the exercise intensity was determined by the player. An indicator of estimated speed relative to the player's average speed (i.e. not considering or giving any indication of augmentation) is shown at the top-right. For safety, the game displayed a red arrow in front of players whenever they moved too much in the room, with opacity indicating urgency, guiding them back towards the centre of the physical play area (Fig. 1c top-centre). The game was implemented in Unity, running on a PC with Intel Core i7 CPU and GTX 1080Ti graphics card.

Procedure. We recruited 28 participants (13 female, 15 male; age 15-75, average 30; 14 with previous VR experience; see Table 1) with unimpaired mobility and additionally four participants with physical mobility impairments (arthritis, acute and chronic pain, reconstructed knee and leg) from the campus of the University of Bath. The study was single-blind to reduce bias, i.e. participants were not told about performance augmentation until after the experiment. Participants were screened using the Physical Activity Readiness Questionnaire (PAR-Q) [112] and randomly assigned to a group (R or RJ). After informed consent, participants completed pre-experiment questionnaires for demographics and RM 4-FM. Participants estimated their average running/walking speed over 5 km, and were shown real-world first-person videos illustrating estimated running speeds to mitigate bias while calibrating VPA [83]. During calibration, $speed_{aug}$ was adjusted so the participant's game experience approximately matched their experience of real-world running. After about 5 minutes of familiarisation with the game, participants played the exergame at each Augmentation (N, L, H), counterbalanced to mitigate order bias. After each condition we measured RPE, IMI and FSQ, giving participants a break of at least 10 minutes. Finally, participants were asked to complete IEQ and RM 4-FM and provide qualitative feedback. Each session took approximately 90 minutes.

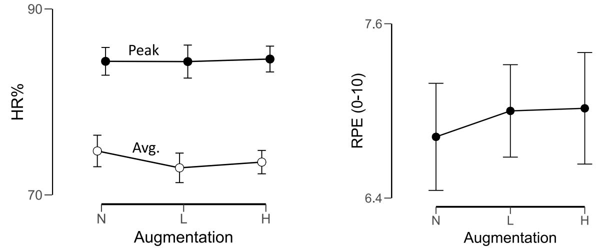

Figure 5: Peak and average heart rate (left) and Rating of Perceived Exertion scores (right) for different augmentation levels.

Hypotheses. Based on pilot testing and related work we posed the following hypotheses:

- **H1** VPA is able to elicit physical activity of at least medium intensity, i.e. ≥65% of maximum HR (RQ2).
- **H2** VPA is immersive, i.e. IEQ scores are significantly above scale mid-point (RQ2).
- **H3** VPA is intrinsically motivating, i.e. at least 'somewhat' interesting/enjoyable (RQ2).
- **H4** VPA increases the intrinsic motivation of the augmented activity (RQ3).
- **H5** VPA increases the perceived competence of the augmented activity (RQ3).

H1-H3 are concerned with the proposed VPA method in general and therefore tested for all levels of Augmentation. The use of the scale mid-point as a meaningful criterion in H2 and H3 is supported by IEQ [16] and IMI measures [49, 79] reported in the literature. For H4 and H5 we consider only the difference between N and H, as L is likely to be severely affected by perception bias [83].

Results

The results are shown in Table 1. The variances in each condition were similar enough and the measurements' distributions close enough to normal, with sufficient sphericity, to warrant analyses of variance (ANOVA).

Performance. HR Avg% is on average above 70% and HR Peak% is on average above 80% in all conditions (Fig. 5 left). RPE is on average above 6 (Fig. 5 right), indicating a 'strong' to 'very strong' perceived exertion. One-sample t-tests with Bonferroni correction show that HR Avg% is significantly above 65%, $t(27) \geq 3.30, p < .01$, HR Peak% is significantly

Table 1: Summary of demographics and results for each group (mean ± std. dev.).

Activity	n	Demographics	Variable	Augmentation (within-participant)		
				None (N)	Low (H)	High (H)
Run Only (R)	14	m=8, f=6	HR Peak%	81.6±15.1	80.7±17.0	81.0±15.4
		age=28±9	HR Avg%	72.4±13.6	70.0±15.3	71.0±14.1
			IMI Enjoyment	5.3± 1.0	5.4± 1.0	5.6± 0.8
		RM4-FM Pre =8.1±3.3	IMI Competence	4.4± 1.6	4.5± 1.8	4.6± 1.6
		RM4-FM Post=8.5±3.6	FSQ Balance	3.5± 0.9	3.5± 1.0	3.7± 0.9
		IEQ=4.9±0.6	FSQ Absorption	4.3± 0.8	4.4± 0.6	4.4± 0.7
Run & Jump (RJ)	14	m=7, f=7	HR Peak%	87.1± 9.1	88.0± 8.7	88.2± 8.6
		age=32±17	HR Avg%	77.0± 8.5	76.3± 8.6	76.1± 8.6
			IMI Enjoyment	4.8± 1.4	5.1± 1.6	5.2± 1.4
		RM4-FM Pre =9.3±3.9	IMI Competence	3.6± 1.9	4.1± 1.3	4.2± 1.2
		RM4-FM Post=10.4±4.0	FSQ Balance	3.4± 1.1	3.5± 0.7	3.7± 0.8
		IEQ=4.9±0.8	FSQ Absorption	4.2± 1.0	4.3± 1.1	4.3± 1.0

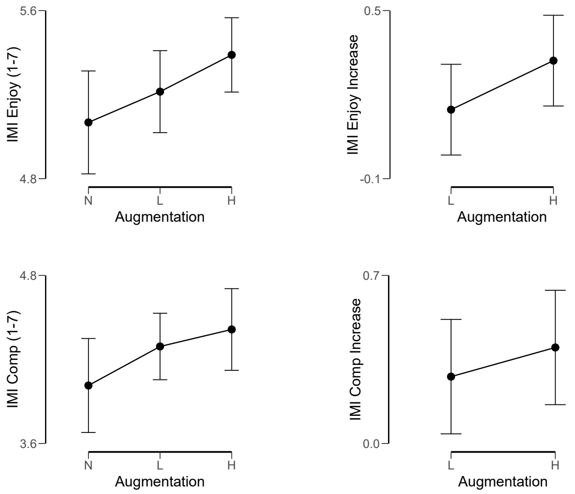

Figure 6: IMI Interest/Enjoyment scores (top-left) and score differences from N (top-right), and IMI Perceived Competence scores (bottom-left) and score differences from N (bottom-right) for different augmentations.

above 75%, $t(27) \geq 3.59, p < .01$, and RPE is significantly above 6, $t(27) \geq 2.78, p < .01$, for all levels of augmentation. This indicates that participants were exercising at a moderate to high intensity [85], so we accept H1. Two-way repeated measures ANOVAs were conducted on the effects of Augmentation (N, L and H) and Activity (R and RJ) on HR Avg%, HR Peak% and RPE. The main effects of Augmentation, $F(2, 52) \leq 1.43, p \geq .25$, the main effects of Activity, $F(1, 26) \leq 2.06, p \geq .16$, and the interaction effects, $F(2, 52) \leq 0.52, p \geq .60$, were not significant.

Immersion. An independent-samples t-test comparing IEQ scores for R and RJ showed no significant difference, $t(26) = 0.09, p = .93$. A directed one-sample t-test of the marginal mean showed IEQ scores were significantly greater than the scale mid-point 4, $t(27) = 6.97, p <= .001$, with a 'large' effect size (Cohen's d=1.32), so we accept H2.

Intrinsic Motivation. Averages of IMI Interest/Enjoyment scores increased with augmentation (Fig. 6 top-left). Directed one-sample t-tests with Bonferroni correction showed that the scores were significantly above scale mid-point for all levels of augmentation (N, L and H), $t(27) \geq 4.56, p < .01$, with 'large' effect sizes (Cohen's d>0.86). This indicates the exergame is at least 'somewhat' interesting/enjoyable, therefore we accept H3. An independent-samples t-test comparing Interest/Enjoyment increase (from N to H) for R and RJ showed no significant difference, $t(26) = 0.42, p = .68$. A one-sample t-test of the marginal mean (Figure 6 top-right) showed the increase in Interest/Enjoyment from N to H was significant, $t(27) = 2.12, p = .02$, with a 'medium' effect size (Cohen's d=0.40), therefore we accept H4. Averages of IMI Perceived Competence scores increased with augmentation (Fig. 6 bottom-left). A Welch's independent-samples t-test comparing Perceived Competence increase (from N to H) for R and RJ showed no significant difference, $t(19.71) = 0.96, p = .35$. A one-sample t-test of the marginal mean (Fig. 6 bottom-right) showed a significant increase in Perceived Competence from N to H, $t(27) = 1.73, p = .048$,

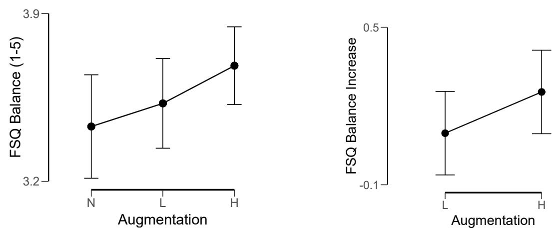

Figure 7: FSQ Balance of Challenges and Skills scores (left) and score differences from N (right) for different levels of augmentation.

with a 'small' effect size (Cohen's d=0.33), so we accept H5. A directed paired-samples t-test showed that RM 4-FM Autonomy Index post-scores were significantly higher than pre-scores, $t(26) = 1.94, p = .03$, with a 'medium' effect size (Cohen's d=0.37).

Flow. Averages of FSQ Balance of Challenges and Skills scores increased with augmentation (Fig. 7 left). An independent-samples t-test comparing Balance of Challenges and Skills increase (from N to H) for R and RJ showed no significant difference, $t(26) = 0.72, p = .48$. A one-sample t-test of the marginal mean (Fig. 7 right) showed the increase in Balance of Challenges and Skills from N to H was significant, $t(27) = 1.92, p = .03$, with a 'medium' effect size (Cohen's d=0.36). Also, averages of FSQ Absorption in the Task scores increased slightly with augmentation; however, an independent-samples t-test comparing increases for R and RJ, $t(26) = 0.29, p = .77$, and a one-sample t-test of the marginal mean, $t(27) = 0.72, p = .48$, were not significant.

Comments and Observations. Participants appeared to enjoy the exergame. Several participants commented positively on their augmented performance. Most participants frequently made considerable movements forward instead of moving on the spot. Participants explained this by immersion, 'forgetting' their physical surroundings. Although all participants learned to keep their movements in place better, forward movement was clearly a safety issue and participants often had to be warned verbally about their position, despite the in game arrow indicators. Participants commented that this negatively affected immersion and flow. Several participants reported limitations of VR affecting them: mild VR sickness, holding the HMD in place during running to avoid discomfort, Kinect tracking problems when moving too much forward, and general unease about physical running/jumping in VR. As a result, some participants chose not to jump over every obstacle. VPA and VR sickness appeared to be uncorrelated: of the two participants who reported symptoms of mild VR sickness, one reported a sense of imbalance during running in VR in general and the other reported dizziness only for the unaugmented condition. Participants appeared to become more comfortable with the VR exergame over time. The four participants who were affected by physical impairments calibrated the game to perform WIP instead of running and just a squatting motion instead of a jump. This worked fairly well, allowing them to use all game mechanics. They noted the usefulness of VPA for making the game accessible, but also requested more features to ensure safety during play. All other participants chose to run instead of WIP for most of the gameplay, but two had to slow down to a walk very briefly due to fatigue.

Discussion

In place running and jumping can be recognised and augmented to create a VR exergame that is exerting (H1), immersive (H2) and enjoyable (H3). Similar to a treadmill [56], such an exergame has to be designed very carefully to address health and safety concerns. Stronger safety cues (e.g. auditory as well as visual), safety barriers around the player, or even a safety harness could help. Similar to a treadmill, it would be useful to implement emergency stop features, e.g. based on position, automatic assessment of a player's balance, and HR. In compliance with norms of fitness instruction [61], an exergame should also encourage players to use low-impact movements if adequate, such as WIP and squatting, which we found to be feasible alternatives to running and jumping. Advances in VR technology, such as lighter HMDs and better tracking, will help make such an exergame popular.

VPA appears able to improve intrinsic motivation, such as enjoyment (H4) and perceived competence (H5), and also improve flow. This is consistent with self-determination theory, which predicts that perceived competence affects intrinsic motivation [98, 114]. It is also consistent with positive psychology, which predicts that a better balance of skills and challenges increases flow, which is an inherently enjoyable state [23, 74]. In principle, VPA could be applied in any VR exergame that allows for such a change in perception, i.e. where perceived performance is not constrained physically. However, it is yet unclear when and how exactly VPA can be applied to good effect. The effect sizes we observed were 'small' to 'medium' – could they be increased with stronger VPA or improved design? Further research could look at different augmentation factors and activities to explore the effects of VPA.

Our results show that VPA may also increase intrinsic motivation for physical activity in general, with RM 4-FM "Motivation for Physical Activity" results indicating a 'medium' effect. Self-determination theory suggests that increasing intrinsic motivation of a physical activity helps to foster a more active lifestyle in general [2, 34, 98, 99]. In line with this, feedforward theory [29–31] and theory on the Proteus effect [124] predict that if players identify with a self model improved by VPA, and if the perceived improvement is realistic, then this will facilitate similarly improved real behaviour. However, in this study we measured only pre-post increases in Autonomy Index scores, which could simply be an effect of the exergame, or even just the exercise, rather than VPA. In order to verify the effects of VPA on motivation for physical activity in general, VPA should be compared against an analogous intervention without augmentation over a longer time.

4 CONCLUSION

We proposed a novel method for virtual performance augmentation (VPA) of running and jumping, using VR to give users the illusion of improved performance. We studied its effects in a VR exergame, coming to the following conclusions:

1. In place walking, running and jumping can be recognised and augmented using only consumer-level VR.
2. VPA can create an exerting, somewhat natural, immersive, enjoyable and accessible exergame experience.
3. VPA can increase intrinsic motivation, perceived competence and flow.

VPA holds promise as a method for making exergames more motivating and accessible, and may help in promoting positive behavioural change. In particular, the application of VPA in rehabilitation is an exciting avenue of future work.

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