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Original Article

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Acute Effects of Heart Rate-Controlled Exergaming on Vascular Function in Young Adults

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Abstract

Objective: Acute and regular moderate-intensity endurance exercise (MIEE) is known to positively affect vascular function. The present study assessed if an exercise session in an innovative exergame called the ExerCube can induce similar vascular reactions as an MIEE session.

Materials and Methods: Twenty-eight healthy recreationally active participants (13 females and 15 males; aged 24.8 ± 3.9 years; with body mass index 23.2 ± 2.3 kg/m^2) completed an exergaming session (EGS) in the ExerCube (25 minutes) and an MIEE session on a treadmill (35 minutes, 65%–70% of maximal heart rate [HR]) in a randomized order. Both before and throughout the 45 minutes after the training sessions, pulse wave velocity (PWV), total peripheral resistance (TPR), stroke volume (SV), and HR were recorded. The study was approved by the Research Ethics Board of the Martin-Luther-Universität Halle-Wittenberg (Medical Faculty of the Martin-Luther-Universität 2019-177).

Results: There were different hemodynamic responses to both types of exercises. PWV was significantly decreased 45 minutes after the EGS ($P < 0.001$). No significant changes were detected after MIEE ($P = 0.109$). TPR was significantly lower after both exercise sessions ($P < 0.01$). Only the EGS resulted in a significant decrease in SV 15 minutes after exercise ($P < 0.001$). The HR was significantly ($P < 0.05$) higher after both exercise sessions. After the EGS, the increase in HR was still significantly higher ($P = 0.011$) 45 minutes after the session. The interaction effects revealed significant differences in PWV (15 minutes, $P = 0.035$; 30 minutes, $P = 0.004$; and 45 minutes, $P < 0.001$), favoring the EGS.

Conclusion: The EGS seems to induce a relevant exercise stimulus that can modulate vascular function. Therefore, this exergame may present an effective tool for prevention of cardiovascular diseases.

Keywords: Exergaming, Moderate endurance exercise, Health, Pulse wave velocity, Total peripheral resistance

Introduction

A sedentary lifestyle and physical inactivity are the leading modifiable risk factors for cardiovascular disease and all-cause mortality.[1] Mortality due to physical inactivity was estimated to have reached over 5.3 million deaths worldwide in 2008.[2] The American Heart Association published a scientific opinion highlighting the associations between physical inactivity and cardiovascular morbidity and mortality.[3] On the other hand, regular physical activity (PA) has a favorable influence on blood pressure (BP),[4] reduces the risk of heart attack,[5] improves endothelial function,[6] increases capillary density,[7] and reduces arterial stiffness and myocardial oxygen demand.[8]

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Although these positive effects of exercise are generally recognized, more than a quarter of adults worldwide do not meet the recommendation of 150–300 min/week of moderate-intensity PA or 75–150 min/week of high-intensity PA.[9,10] Even though participation in regular exercise is influenced by various personal, social, and environmental factors, the lack of motivation appears to be one of the most common barriers.[11] In this context, the so-called exergames have great potential, enabling a joyful and engaging training experience.[12]

Exergames are interactive video games that integrate physical movements into the game and thus enable an active gaming experience.[13] By combining electronic entertainment and physical exercise, these games create new opportunities to expand PA in different settings.[14] The question arises as to whether exergaming is a suitable and effective training approach for cardiovascular disease prevention.

Current research indicates that although exergaming increases energy consumption, it does not induce adequate exercise intensities resulting in relevant physical and health-related adaptations.[15–19] This may be because most exergames lack an effective training concept.[20]

With the ExerCube, a new exergame model is on the market, combining innovative software and hardware design with a modern and holistic training approach.[21,22] This immersive fitness game setting enables the user to adjust the training intensity individually, thus triggering an adequate training stimulus. Due to the individualized training approach, the ExerCube may not only present a promising tool for the general population but may also be applicable for cardiovascular disease prevention.

The present study determined whether the ExerCube is an effective training approach that triggers relevant effects on the cardiovascular system, similar to conventional moderate-intensity endurance exercise (MIEE). The results may add important information regarding the application of exergames as a tool in cardiovascular disease prevention. To determine the effects on the cardiovascular system, parameters that can provide information about blood flow, arterial stiffness, or elasticity, as well as different pressure conditions in the large arteries, are evaluated.

Therefore, the acute effects of an exergaming session (EGS) in the ExerCube on pulse wave velocity (PWV) and total peripheral resistance (TPR), as well as on stroke volume (SV) and heart rate (HR), were compared with those of an acute MIEE session on a treadmill.

Due to their higher predictive value regarding future cardiovascular events, these hemodynamic parameters are becoming increasingly important in cardiovascular diagnostics and risk stratification.[23]

Materials and Methods

Participants

Twenty-eight, healthy, normotensive recreationally active participants (13 females and 15 males; aged 24.8 ± 3.9 years; with body mass index [BMI] 23.2 ± 2.3 kg/m^2) were recruited. Exclusion criteria were acute and chronic cardiovascular diseases, injuries of the musculoskeletal system, and extreme forms of nutrition. None of the participants had antihypertensive or other cardiovascular medication or had previously received cardiovascular treatment. None of the participants had experience with the ExerCube.

All female participants had regular menstrual cycles and no history of menstrual distress.

Before the study, all participants were informed about the content and structure of the study and gave their written consent.

The study was conducted in accordance with the Helsinki Declaration and approved by the Research Ethics Board of the Martin-Luther-Universität Halle-Wittenberg (Medical Faculty of the Martin-Luther-Universität 2019-177).

Study design

The study design consisted of a baseline examination and two exercise interventions held at least 48 hours apart. The order of the exercise interventions was randomized using the random sequence generator software at www.random.org

Participants were instructed to abstain from caffeine and nicotine for at least 4 hours before the tests, not eat or drink anything for at least two hours, and refrain from vigorous PA and alcoholic beverages for at least 12 hours before each examination.

To reduce the circadian influence, care was taken to ensure that each test was performed at the same time of day.

Since hemodynamic responses to exercise are more pronounced in the early follicular phase, the tests for all females were scheduled so that they did not fall within this time frame.[24]

Baseline assessments

Participants completed basic questionnaires assessing medical history and habitual PA. In addition, hemodynamic readings were conducted to familiarize the participants with the procedure.[25]

The body height was measured barefoot with a wall-mounted scale to the nearest 0.5 cm. Body mass was determined with an accuracy of 0.1 kg using an electronic balance (BC-545 InnerScan; Tanita, The Netherlands). The waist circumference was measured with a nonelastic measuring tape placed around the waist of the upright participant between the lowest rib (costal arch) and the upper edge of the hip bone (iliac crest).

To determine the individual maximum HR (HRmax), the subjects completed a stepwise incremental test until voluntary exhaustion on a treadmill (h/p/cosmos; Pulsar 4.0, Germany). According to the individual training status, the initial speed was set between 7.5 and 10.5 km/h, which was increased every 3 minutes by 1.5 km/h. Between each stage, there was a 1-minute period of passive rest to draw lactate samples. The HR was continuously monitored using an HR monitor (Polar Electro OY, Kempele, Finland).

The enzymatic amperometric method (Dr. Mueller; Super GL Ambulance, Germany) was used to assess blood lactate concentrations. Data were processed with the software, WinLactat 3.1 (Mesics, Germany). Individual threshold values were derived from the lactate curve using the Dickhuth model.[26]

Hemodynamic measurements

After a 15-minute period of supine rest, at least two hemodynamic measurements were carried out on the right upper arm using custom-fit BP cuffs. The PWV, TPR, SV, and HR were recorded using the Mobil-O-Graph (24 PWA Monitor; IEM, Stolberg Germany), a clinically validated device for hemodynamic measurements.[27]

After the respective training sessions, hemodynamic parameters were recorded repeatedly (15, 30, and 45 minutes) while resting in a supine position. All measurements were performed by the same trained staff member in a temperature-controlled room (23.5°C ± 0.5°C).

ExerCube

The ExerCube is an immersive and physically and cognitively challenging functional fitness game setup. An HTC Vive motion tracking system tracks player movement using trackers attached to the player's wrists and ankles. To ensure an engaging and effective training experience for a wide range of players with different abilities, the ExerCube continuously adapts the game difficulty level to fitness and cognitive abilities of the player.[22]

In this study, participants played the game ''Sphery Racer,'' a single-player game experience designed for the ExerCube setting. The player navigates an avatar by performing various movement tasks (e.g., squats, lunges, punches, and burpees). The game implements five levels, with gradually increasing difficulty and complexity. The levels are interspersed by short (≈30 seconds) rest periods. The game starts with a low to moderate intensity and gradually increases until a high-intensity exercise is reached.

Throughout the game, both in-game performance and HR are monitored. To ensure optimal cognitive and physical stimuli, game difficulty and speed are adjusted accordingly. Whenever subjects accumulate too many mistakes or reach a given HR (90% of HRmax), the speed of the game slows down. A more detailed description can be found in the study by Martin-Niedecken et al.[21,22] The HR was recorded continuously with a Polar HR monitor throughout the exercise session.

To determine fluid loss, body mass was assessed before and after the training session.

Moderate-intensity endurance exercise

MIEE was carried out on a treadmill (h/p/cosmos; Pulsar 4.0, Germany) for 35 minutes. After a 5-minute warm-up at 5.5 km/h, the speed of the treadmill was adjusted according to the individual aerobic threshold. Thereafter, the speed was continuously adjusted to achieve an individual HR of ~65%–70% of their HRmax during the entire training session. Throughout the session, HR was monitored with a Polar HR monitor. Body mass was determined before and after the MIEE session.

Statistical analyses

An a priori power analysis utilizing G*power (Version 3.1.2; Heinrich Heine Universität, Dusseldorf, Germany) indicated that a sample size of 24 subjects would provide sufficient power to observe differences, assuming a large effect size. The subjects' anthropometric data were analyzed with Microsoft Excel 2013 and presented as the mean and standard deviation.

All other statistical analyses were carried out using R (Version 3.5.3). A two-sided Wilcoxon test was used for connected samples due to the nonsymmetrically distributed samples. Variables are shown as the median and first and third quartiles. The level of significance was set at $P < 0.05$.

Results

All participants completed the examination without any adverse events. Their characteristics are shown in Table 1. On average, the participants were engaged in 7.1 ± 3.4 hours of physical exercise per week. According to the BMI, four subjects were classified as overweight.[28] Concerning the waist-to-height ratio, two of the subjects included showed values within the overweight range.

Pulse wave velocity

PWV was elevated until 30 minutes after the EGS before declining below resting values (Table 2). For the MIEE, a significant increase in PWV 15 minutes after the exercise session was detected (Table 2). The interaction effects between both exercise sessions revealed significant differences in favor of the EGS 15 ($P = 0.035$), 30 ($P = 0.004$), and 45 ($P < 0.001$) minutes after the exercise session (Fig. 1).

Total peripheral resistance

Compared with the resting value, TPR was significantly lower 15, 30, and 45 minutes after both exercise conditions (Table 2). There were no significant differences between the two exercise protocols (Fig. 2).

Stroke volume

The SV decreased significantly 15 minutes after the EGS and then returned to resting values (Table 2). The MIEE induced no significant changes in SV (Table 2). There were significant interaction effects between the two conditions 15 minutes after exercise ($P = 0.007$) (Fig. 3).

Heart rate

The EGS resulted in a significant increase in HR 15, 30, and 45 minutes after the training (Table 2). The MIEE only resulted in a significant increase in HR 15 and 30 minutes postexercise (Table 2). The interaction effects revealed a significantly stronger increase in HR 15 ($P = 0.001$) and 30 ($P = 0.041$) minutes after the EGS compared with the MIEE ($P = 0.001$) (Fig. 4).

Discussion

To the best of our knowledge, this is the first study to compare the effects of an acute EGS in the ExerCube and MIEE on vascular function in adults. The study shows that a single EGS significantly reduces PWV in healthy adults. In contrast, the significantly longer MIEE did not lead to any significant changes in PWV.

Table 1. Subjects' Characteristics

	Mean value and SD
Age (years)	24.8 ± 3.9
Gender (f/m)	13/15
Body mass (kg)	68.9 ± 10.7
Height (cm)	171.9 ± 9.7
Body mass index (kg/m^2)	23.2 ± 2.3
Waist-to-height ratio	0.4 ± 0.1

SD, standard deviation.

Table 2. Pulse Wave Velocity, Total Peripheral Resistance, Stroke Volume, and Heart Rate at Rest Before and 15, 30, and 45 Minutes After Exercise

	Exergaming session	P-*Value*[a]	*Moderate-intensity endurance exercise*	P-*Value*[a]
PWV (m/s)				
At rest (reference)	5.25 (4.94, 5.49)		5.07 (4.89, 5.45)	
15 minutes	5.20 (5.99, 5.55)	$P = 0.694$	5.20 (4.97, 5.73)	$P = 0.006$
30 minutes	5.30 (4.80, 5.50)	$P = 0.037$	5.20 (4.90, 5.60)	$P = 0.151$
45 minutes	5.10 (4.80, 5.32)	$P < 0.001$	5.30 (4.88, 5.53)	$P = 0.109$
TPR (s*mmHg/ml)				
At rest (reference)	1.17 (1.04, 1.31)		1.14 (1.05, 1.37)	
15 minutes	1.03 (0.96, 1.14)	$P = 0.009$	1.06 (0.95, 1.21)	$P = 0.008$
30 minutes	0.91 (0.83, 1.15)	$P < 0.001$	1.04 (0.82, 1.18)	$P = 0.003$
45 minutes	0.98 (0.82, 1.19)	$P = 0.005$	97 (0.86, 1.19)	$P = 0.004$
SV (ml)				
At rest (reference)	82.4 (68.70, 94.53)		80.2 (70.24, 90.25)	
15 minutes	65.6 (56.00, 73.30)	$P < 0.001$	76.2 (66.65, 88.15)	$P = 0.386$
30 minutes	80.8 (66.85, 94.57)	$P = 0.488$	86.9 (69.60, 95.68)	$P = 0.398$
45 minutes	79.2 (66.53, 95.10)	$P = 0.526$	87.7 (72.10, 99.25)	$P = 0.170$
HR (bpm)				
At rest (reference)	61.5 (53.62, 65.88)		59.5 (55.38, 64.00)	
15 minutes	83.5 (71.00, 89.00)	$P < 0.001$	69.0 (63.50, 81.00)	$P < 0.001$
30 minutes	69.5 (62.75, 78.75)	$P < 0.001$	66.0 (59.25, 69.75)	$P = 0.001$
45 minutes	67.5 (57.75, 76.00)	$P = 0.011$	65.5 (58.00, 69.75)	$P = 0.070$

[a]Exact Wilcoxon test—comparison with resting value (reference). Variables are shown as the median and first and third quartiles. HR, heart rate; PWV, pulse wave velocity, TPR, total peripheral resistance; SV, stroke volume.

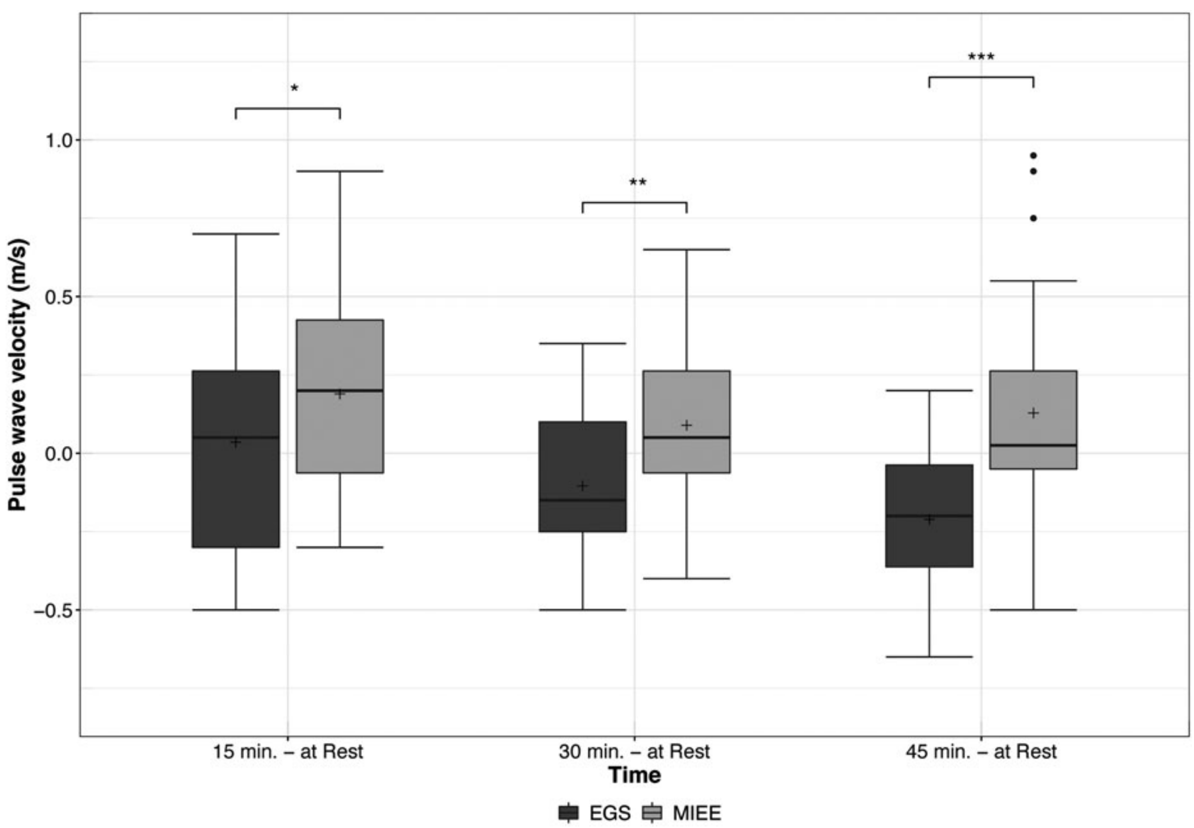

FIG. 1. Changes in PWV from rest before and 15, 30, and 45 minutes after exercise, stratified according to the type of exercise (EGS and MIEE). Interaction effect $*P \leq 0.05$; $**P < 0.01$; and $***P < 0.001$. EGS, exergaming session; MIEE, moderate-intensity endurance exercise.

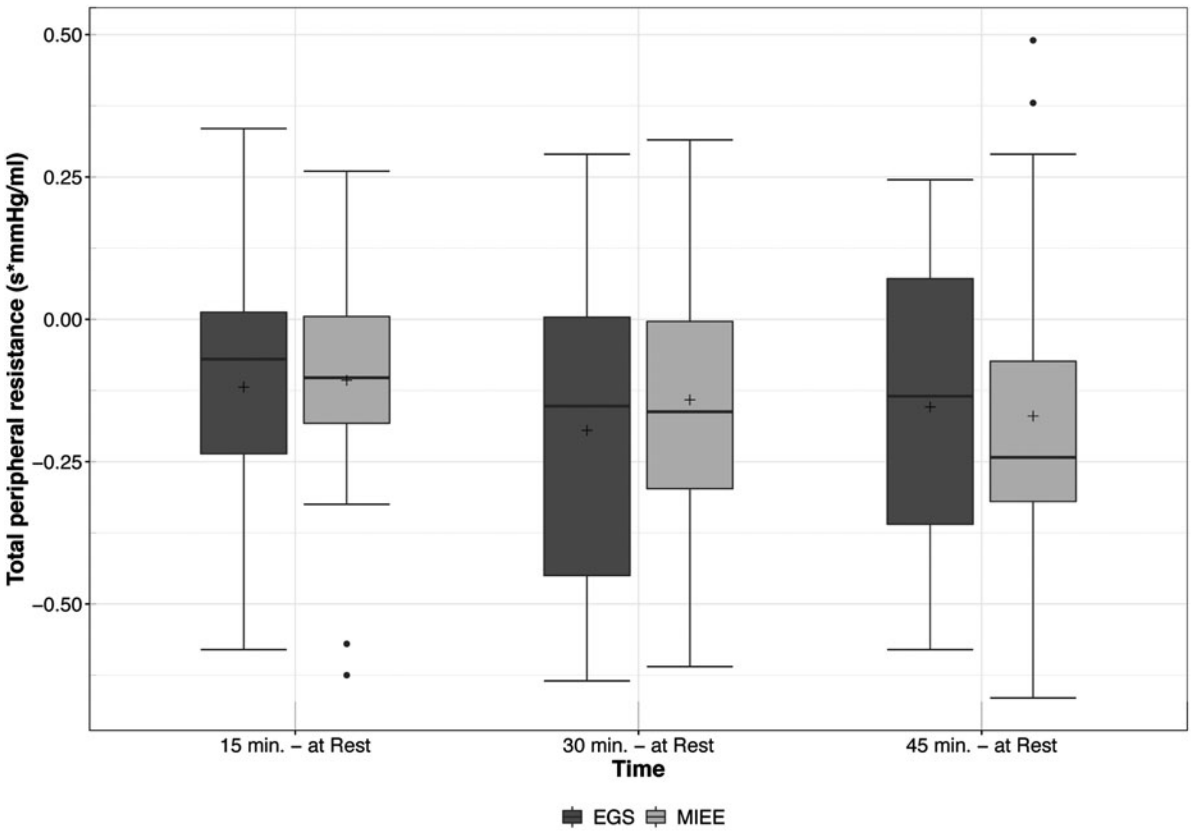

FIG. 2. Changes in TPR from rest before and 15, 30, and 45 minutes after exercise, stratified according to the type of exercise (EGS and MIEE). EGS, exergaming session; MIEE, moderate-intensity endurance exercise.

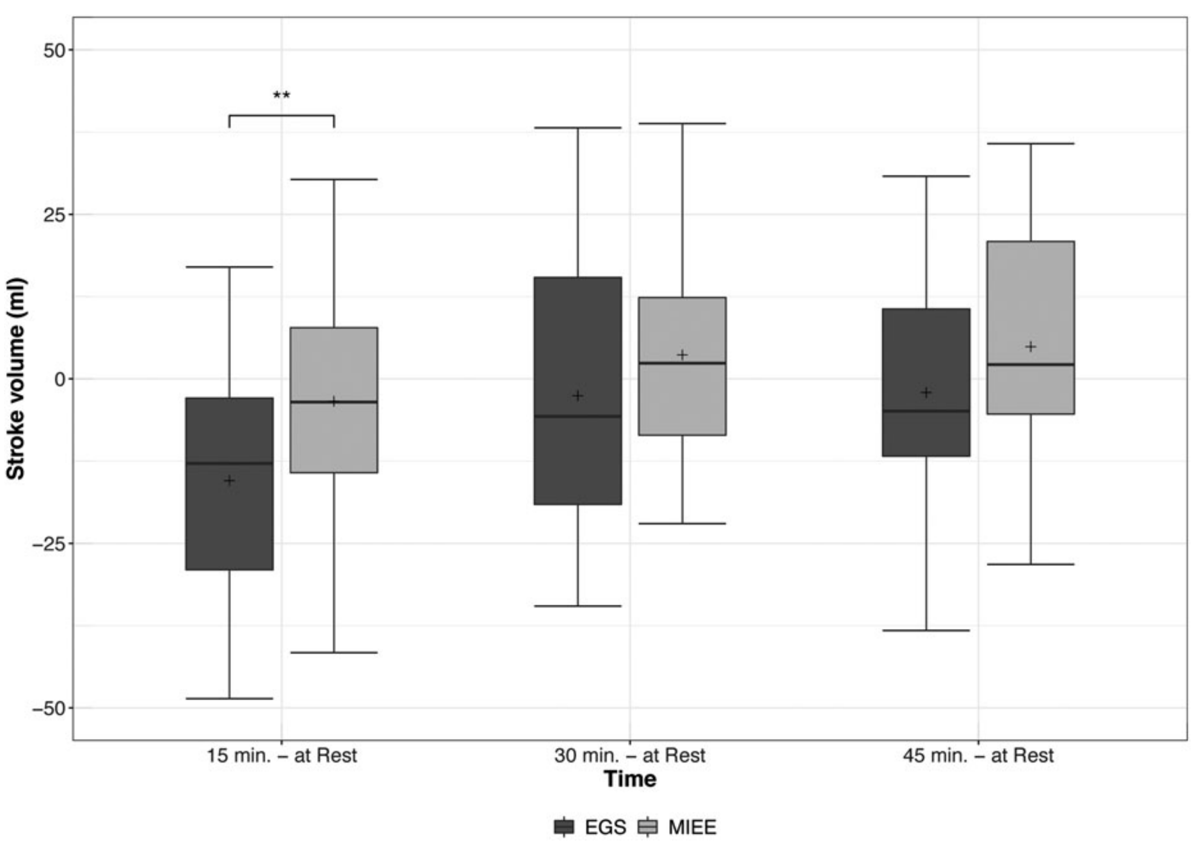

FIG. 3. Changes in SV from rest before and 15, 30, and 45 minutes after exercise, stratified according to the type of exercise (EGS and MIEE). Interaction effect $^{**}P < 0.01$. EGS, exergaming session; MIEE, moderate-intensity endurance exercise.

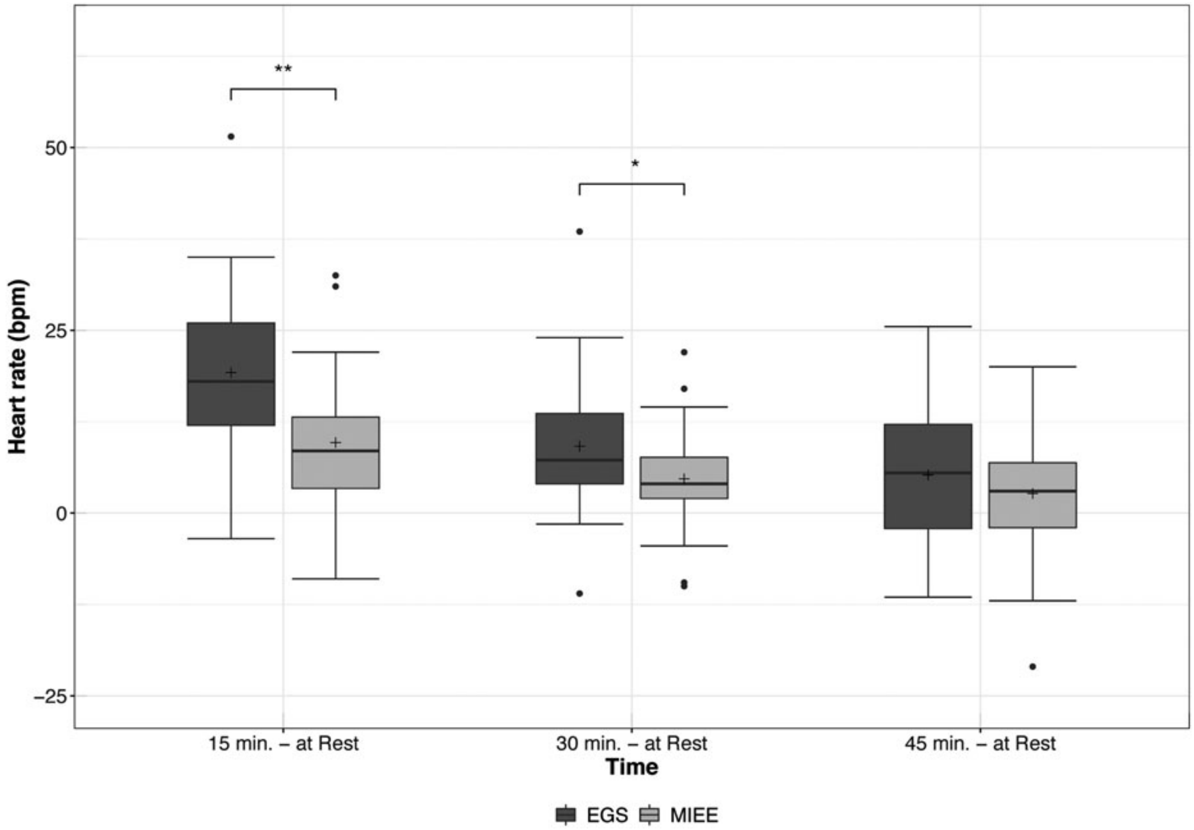

FIG. 4. Changes in HR from rest before and 15, 30, and 45 minutes after exercise, stratified according to the type of exercise (EGS and MIEE). Interaction effect $*P \leq 0.05$ and $**P < 0.01$. EGS, exergaming session; MIEE, moderate-intensity endurance exercise.

The PWV, which describes the speed of the central pulse wave and reflects arterial stiffness, is considered as an early indication of the severity of existing structural vascular alterations and subsequent cardiovascular risks.[29] The predictive value of the PWV regarding cardiovascular events is said to be higher than general risk parameters such as peripheral BP.[30–32] The positive effects of regular PA on PWV have already been confirmed.[33,34] In addition to long-term effects, an acute bout of exercise can also positively modulate PWV.[35]

Evidence further supports the hypothesis that the chronic beneficial influence on hemodynamics from engaging in long-term exercise programs is largely due to the summative effects of changes observed after each bout of exercise.[36]

Various training protocols have been shown to reduce PWV in a subsequent rest phase to a similar extent as the EGS.[37,38] Interestingly, the MIEE in the present study did not lead to any significant changes in the PWV. This contrasts with the study by Milatz et al.,[39] who found a significant reduction in PWV after a single aerobic training session. However, compared with the present study, Milatz et al. used a significantly longer exercise protocol.[39]

It seems that the duration of the MIEE was too short to induce relevant responses in PWV. This is in line with a recent study assessing the acute effects of different durations of moderate-intensity exercise,[40] where longer exercise protocols resulted in a more substantial reduction of BP and significantly improved endothelial function.

Contrastingly, there was a much stronger reduction in PWV after the significantly shorter EGS. This can be attributed to the higher exercise intensity. During the MIEE, the mean HR reached 126.9 ± 8.1 bpm, corresponding to $65.6\% \pm 3.9\%$ of HRmax. Throughout the EGS, the mean HR reached 166.8 ± 11 bpm, which corresponds to $85.9\% \pm 4.3\%$ of HRmax.

Previous research shows that exercise of higher intensity leads to more pronounced effects on macrovascular and microvascular function than moderate endurance exercise.[38] The higher exercise intensity during the EGS may result in higher oxygen demand in working muscles, increasing peripheral blood flow. The blood flow increase represents a mechanical stimulus in the vascular endothelium, resulting in a subsequent release of vasoactive mediators.[41,42]

In addition to exercise intensity, the different exercise types could also have a modulating effect. The EGS is characterized by intermittent bouts of exercise interspersed by short passive rest periods. Studies could show that intermittent exercise results in a larger stimulus for vascular adaptations compared with continuous exercise of the same intensity and duration.[43,44] This is probably due to higher fluctuations in cardiac output and thus larger blood flow variations, with greater pulsate and shear stress, resulting in a more pronounced nitric oxide release.[43]

It is generally agreed that hemodynamic changes after acute exercise are caused by a reduction in TPR, resulting in increased venous pooling, wherein the left ventricular preload is reduced.[42] This, in turn, leads to reduction in SV. Although HR is increased after acute exercise, the resulting increase in cardiac output cannot compensate for the decline in TPR.[41,45]

A reduction in TPR after an acute bout of exercise is confirmed in a meta-analysis by Cornelissen and Fagard.[46] In addition, Izdebska et al.[47] could show a significant reduction in TPR after 20 minutes of moderate exercise in hypertensive and normotensive men, lasting up to 20 minutes. Piepoli et al.[48] could show a greater reduction in TPR after maximum exercise training compared with moderate exercise training.

In the present study, both exercise protocols resulted in a significant reduction in TPR. Although the mean reduction in TPR was more pronounced after the intensive EGS compared with MIEE, the differences did not reach statistical significance.

Concerning SV, a significant drop 15 minutes after the EGS could be detected. After MIEE, there was no significant change, respectively. A possible explanation for the drop in SV 15 minutes after the EGS may be due to exercise-induced cardiac fatigue. Research could show that acute exercise promotes temporary exercise-induced cardiac fatigue that especially affects the right ventricle as well as, to a lesser extent, the left ventricle by increasing the right ventricular afterload.[49]

In the present study, cardiac contractility seemed to be more impaired after the EGS than after the MIEE session, which may again be attributed to differences in exercise intensity. Ketelhut et al.[50] confirmed a supposed cardiac fatigue after a long aerobic exercise. In contrast to the present investigation, this was caused by a decrease in cardiac output and an increase in TPR. As mechanisms of temporary reduction in cardiac performance, possible myocardial ischemia, alterations in beta-receptor reactivity, changes in cardiac autonomous modulation, and changes in intrinsic myocardial relaxation must be discussed.[51,52]

Another mechanism that has often been debated to influence hemodynamics after exercise is a predominance of vasovagal balance.[53] However, this could not be confirmed in the present study. The participants showed a significant increase in HR throughout the 45 minutes of recovery after the EGS. With the MIEE, the HR was significantly higher 15 and 30 minutes after exercise.

It seems that the EGS, which induces higher exercise intensities and engages larger muscle mass through whole-body movements, has the potential to lead to stronger hemodynamic reactions. According to our knowledge, only few studies have evaluated the effects of exergaming on different hemodynamic parameters. Monteiro-Junior et al.[54] evaluated the effect of a 10-minute exercise with Nintendo® Wii™ ''Free Run'' on hemodynamic responses in healthy inactive women. They found that the exergame triggered acute hemodynamic changes with a decline in peripheral BP.

These results are supported by de Brito Gomes et al.,[55] who reported a significantly lower BP 30 minutes after playing different exergames on the Xbox® 360 Kinect. Mills et al.[56] compared the effects of high-intensity and low-intensity exergaming with the Xbox 360 Kinect in children and found that flow-mediated dilation of the brachial artery improved after high-intensity exergaming.

Another study examined the acute hemodynamic effects of virtual reality-based exergames in patients undergoing cardiac rehabilitation.[57] The effects of the exergame-based therapy were comparable with general cardiovascular rehabilitation consisting of whole-body exercises for the upper and lower limbs and endurance exercises on a treadmill.

Preliminary studies have also assessed the effects of long-term exergaming interventions on BP. Staiano et al.[58] evaluated a 24-week home-based exergaming intervention in overweight and obese children. The authors could show improvements in systolic and diastolic BP. Jo et al.[59] were able to show that an exergaming intervention improved endothelial function in postmenopausal women with high cardiovascular risk to a similar extent as traditional aerobic exercise. Other studies in adults[60,61] found no apparent beneficial effects on BP after different exergaming interventions.

Although numerous studies have identified exergames as a promising approach to promote PA,[18] the literature remains ambiguous whether exergames elicit intensity levels that lead to relevant physiological responses. The present study reveals that properly designed exergames can positively modulate hemodynamic parameters and thus reduce the cardiovascular risk profile. Therefore, the results add important physiologic information regarding the application of exergaming as a tool in cardiovascular disease prevention.

Based on these results, exergames may present an innovative alternative to classical exercise programs and can improve patient adherence to treatment. Furthermore, the game mechanics of the ExerCube provides valuable information for game designers developing future exergames.

Limitations

There are a few limitations that warrant discussion. First, only healthy participants were recruited in this study. Further studies including different populations, especially risk patients, should be carried out. Second, the results in the present study refer to a specific exergame. Other exergames, especially those that are less intense, would probably lead to different effects. Third, only the effects of an acute EGS were evaluated in the present study. Further investigations that analyze the long-term effects of a regular EGS in the ExerCube are warranted.

Conclusions

It can be concluded that the ExerCube is superior to acute MIEE in the favorable influence on hemodynamic parameters. Due to its individualized training, the ExerCube can probably serve as a timely, efficient, and motivating exercise approach for prevention and rehabilitation of cardiovascular diseases.

Authors' Contributions

R.G.K., K.K., and S.K. conceived the original idea. K.K. and K.H. supervised the project. E.K., R.G.K., S.K., and K.K. designed the study. L.R. and E.K. performed the measurements. A.L.M.-N. designed the exergame intervention and gave technical support. E.K. processed the experimental data and performed the analysis. E.K., S.K., and R.G.K. drafted the manuscript and designed the figures. K.K., R.G.K., E.K., A.L.M.-N., and K.H. aided in interpreting the results and worked on the manuscript. All authors provided critical feedback and helped shape the research, analysis, and manuscript. All authors have read and approved the final version of the manuscript and agree with the order of presentation of the authors.

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Author Disclosure Statement

The authors declare that they have no conflicts of interest. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Besides being a Senior Researcher at the Zurich University of the Arts, A.L.M.-N. is also Co-Founder and CEO of the spin-off company, Sphery Ltd., which further developed the ExerCube based on the results of her R&D work. No revenue was paid to A.L.M-N., Sphery, or the research institutions.

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