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Is fetal well-being jeopardised during high-intensity interval training?

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ABSTRACT

Objectives To explore the acute effects of high-intensity interval training on fetal heart rate (FHR) and uteroplacental blood flow.

Method Elite (n=10) and recreational athletes (n=50) participated in an experimental laboratory study involving 5×5 min intervals of high-intensity exercise on both a treadmill and cycle ergometer, with a 4 min pause between intervals for measurement of FHR and uteroplacental blood flow. Target intensity was 17 on Borg's rating of perceived exertion (RPE) scale and 90% of estimated maximal maternal heart rate (MHR_{max}).

Results Mean exercise intensity was 16.4 (SD 1.0) RPE and 89.4 (SD 3.8) % of MHR_{max} during running and 16.0 (SD 1.0) RPE and 84.6 (SD 5.0) % of MHR_{max} during cycling. Mean FHR was 140.9 (SD 27.4) beats per minute (bpm) during pauses between running bouts and 148.9 (SD 16.0) bpm during pauses between cycling bouts. Six cases of prolonged fetal bradycardia (<100 bpm for >3 min) occurred during running, leading to the termination of exercise. The mothers exercised at 17–18 on Borg's RPE scale and 86.4%–92.6% of MHR_{max} in these cases. All cases were normalised within 8 min of ending the protocol. There were no cases of prolonged fetal bradycardia during cycling. Exercise was terminated for three women during running and two women during cycling due to fetal tachycardia (≥180 bpm for >4 min during rest).

Conclusion Despite cases of fetal bradycardia and tachycardia, our results indicate that highly active women can engage in multiple intervals of high-intensity interval training without apparent harm to fetal well-being.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Moderate-intensity exercise during pregnancy is safe and widely recommended by global physical activity guidelines to support maternal and fetal health.

⇒ Current guidelines advise against high-intensity exercise during pregnancy due to insufficient empirical evidence supporting its safety.

WHAT THIS STUDY ADDS

⇒ This is the largest study to date on the acute effects of high-intensity exercise on fetal heart rate and uteroplacental blood flow.

⇒ This study demonstrates that high-intensity exercise was well tolerated by pregnant elite and recreational athletes, with any instances of fetal bradycardia and tachycardia resolving quickly.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ These data provide valuable insights that can guide athletes, coaches and healthcare providers in creating safe, evidence-based training plans during pregnancy.

⇒ These findings will help to inform the development of evidence-based guidelines for safely incorporating high-intensity exercise during pregnancy.

INTRODUCTION

Moderate-intensity exercise during pregnancy is safe and beneficial for both the pregnant woman and the developing fetus and is broadly accepted in national and international guidelines.[1–6] In contrast, the safety of high-intensity exercise during pregnancy remains a more controversial issue.[7] It has been hypothesised that high-intensity exercise temporarily redistributes blood flow, prioritising working skeletal muscle over internal organs, including the uterus and placenta. This may result in transient reductions in oxygen and nutrient delivery to the fetus.[8] However, evidence to confirm this hypothesis is limited. Two recent studies observed normal fetal heart rate (FHR) during repeated short bouts (20 s to 1 min) of near-maximal to maximal exertion.[9 10] In contrast, experimental studies on progressively increasing intensity (2 to 5 min stages) have found that intensive training at >90% of maximal maternal heart rate (MHR_{max}) may lead to transient fetal bradycardia.[11 12]

For many athletes, peak fertility coincides with the years of peak athletic performance. In recent years, increasing numbers of female athletes have decided not to postpone having children until they end their careers, thereby challenging stereotypes about combining elite sports and pregnancy.[13] Despite the lack of consensus and empirical data on the safety of intensive exercise during pregnancy, pregnant elite and recreational athletes continue to train during their pregnancies,[14] with little information to guide them and their healthcare providers on how to train safely and maximise performance without jeopardising fetal health. Addressing this knowledge gap is crucial for the development of evidence-based guidelines. Hence, this study investigated the acute effects of high-intensity treadmill running and ergometer cycling on FHR and uteroplacental blood flow in elite and recreational athletes.

METHOD

Study design

This investigation was part of the Strong Mama project, an experimental laboratory study to explore acute fetal and maternal physiological responses to high-intensity interval training and heavy-load resistance training in elite and recreational athletes. The study occurred at the Norwegian School of Sport Sciences in Oslo, Norway, between October 2022 and October 2023.

Participants

Pregnant elite and recreational athletes between gestation weeks 26 and 35, with a single pregnancy and the ability to understand verbal and written Norwegian or English, were eligible to participate. Following the consensus set by the IOC expert committee,[6] we define an elite athlete as an individual who is a member of any national team or other high-level representative team (eg, elite league player for team sports such as handball and football) in any sport organised by a National Sports Federation. Recreational athletes were women who also exercised regularly but were not members of any high-level representative team. Elite and recreational athletes exercised for ≥240 minutes/week for fitness and competition, including high-intensity exercise sessions and/or heavy-load resistance training for at least 2 years before pregnancy.

There were no age or parity-related inclusion criteria. In compliance with Norwegian guidelines on antenatal care, all participants had a routine ultrasound at around 18 weeks of gestation, and women were excluded if they experienced any medical or obstetric contraindications during baseline selection.[2]

Elite athletes were recruited in collaboration with the Norwegian Olympic Sports Centre and national team doctors and support teams at various sports federations. Recreational athletes were recruited through social media, newspaper articles, healthcare clinics in Oslo and word of mouth.

As few studies have investigated high-intensity exercise during pregnancy, data for power calculations are lacking. Hence, a convenience sample of 60 women was chosen for the project, vastly exceeding previous research participant counts.[9–12] 212 women (12 elite and 200 recreational athletes) expressed interest in participation and were contacted by the research team. 28 were excluded due to no longer meeting the inclusion criterion of ≥240 min of exercise per week at 26–35 weeks of gestation. None were excluded due to medical or obstetric contraindications. The first 60 of the remaining 184 women were included.

Protocols and data collection

The running, cycling and ultrasound procedures were based on the protocol developed by Salvesen *et al*.[11] Measures were completed over 2 consecutive days: treadmill running on day 1 and ergometer cycling on day 2. An exercise physiologist conducted all exercise sessions, and a medical doctor was always present. The sessions were conducted at ~20°C.

Running

After a 10 min warm-up at a progressively increasing pace, the 45 min protocol was designed to have athletes run five 5 min high-intensity intervals on a treadmill (Woodway, Weil am Rhein, Germany or SPIRIT FITNESS CT900) or run to volitional fatigue, with a 4 min pause between each interval. During each interval, participants were asked several times to rate their perceived intensity using Borg's rating of perceived exertion (RPE) scale (6–20),[15] ensuring the pace remained appropriate. The target RPE was 17 out of 20, corresponding to 'very hard' exercise. At the end of the interval, participants provided a final RPE to reflect their perception of the overall intensity of the interval. MHR was continuously monitored using a Polar H10 sensor and chest strap. A target of 90% of age-predicted maximum MHR (MHR_{max}) was chosen to meet the criterion for 'high intensity' while remaining below the suggested safety threshold of 90% MHR_{max}.[11] This corresponded to 180 beats per minute (bpm) for participants aged 20–29 years and 176 bpm for those aged 30–39 years.[9] In cases of discrepancies between RPE and MHR, meeting target RPE was prioritised due to the limitations of using MHR as a reliable indicator of intensity. MHR_{max} can vary considerably between individuals, and pregnancy-related physiological changes may further affect heart rate responses.[16,17] As the participants were experienced athletes, RPE provided a more consistent and individualised measure of exertion. The pace corresponding to the target intensity was established during the first interval and adjusted as needed in subsequent intervals to maintain the target RPE. RPE was not required to be at the target for the entire 5 min interval as intensity gradually increased, but the aim was to reach the target intensity as quickly as possible to maximise the time spent at high intensity. For analyses, the final recorded values for MHR and RPE for each interval were used. During the 4 min pause between intervals, 1 min was allocated for transitioning between the treadmill and the semi-recumbent supine position. In contrast, the remaining 3 min were used for the ultrasound measurements (see below).

Stationary bicycling

The cycling protocol was similar to the running protocol, with 5×5 min of high-intensity intervals on a cycle ergometer (Lode, Groningen, Netherlands). Ultrasound measurements (see below) were conducted in the same manner.

Ultrasound protocols

The ultrasound measurements were done by an obstetrician gynaecologist (OBGYN) trained in maternal-fetal medicine using colour Doppler ultrasound before, during pauses and after the exercises with a Voluson (version E8, E10 or E22) device (GE Healthcare, Oslo, Norway) and an XDclear Probe (GE Healthcare). The athletes were in a semi-recumbent supine position (approximately 30°) during the ultrasound assessments. Before initiating the warm-up, the normality of fetal growth, amniotic fluid volume, blood flow in the umbilical and uterine arteries and biophysical profile were assessed, and all fetuses were confirmed to be within normal parameters.

The umbilical artery pulsatility index (PI) and FHR were assessed in a free loop of the umbilical artery. The Doppler waveform was required to be normal, with no reversed or absent flow. The PI was evaluated based on Acharya *et al*.[18] The normal FHR range is 110–150 bpm (110–160 at gestational age <32 weeks). Fetal tachycardia during high-intensity exercise is normal and expected, but was required to be below pathological levels (<180 bpm) for the athlete to continue exercising.[19] In the current study, prolonged bradycardia was defined as FHR of <110 bpm for >3 min (min), as durations shorter than this would be considered a deceleration rather than bradycardia.[20] Prolonged tachycardia was defined as FHR of ≥180 bpm for more than 4 min, based on the interval pause in the exercise protocol. If the fetus showed signs of prolonged bradycardia or tachycardia during the pause between intervals, the protocol was stopped, and FHR was monitored until it normalised. This did not exclude the participant from continuing the overall project, although the interval protocol was discontinued for that session.

Uterine artery PI was assessed on both sides when it crossed the internal iliac artery. Colour Doppler was used to identify the uterine arteries and optimise the insonation angle (kept as close as possible to zero). During the baseline measurements, a reference mark was set at the probe's location to ensure consistent probe placement during all exercise measurements. Callipers were placed on the inner vessel wall, and the mean diameter was used throughout the exercises.

The pause was set to 4 min but extended if needed to get good-quality measurements. After each exercise interval, as many measurements as possible were recorded. Blood flow in the umbilical artery and the right and left uterine arteries was recorded in a repeated sequence, with at least two complete recordings from each vessel during the pause. The first FHR and first umbilical artery PI value and the technically best recordings from each uterine artery were used when evaluating fetal well-being. A final ultrasound measurement of the FHR and umbilical artery PI was conducted after 10–30 min of rest following the end of the protocol. If the athlete experienced any signs of concern or abnormal FHR, she was referred to the gynaecological and obstetrical department of the woman's birthing hospital.

Pilot study

Due to the limited evidence on the safety of high-intensity exercise in pregnancy, we pretested the protocol with the first 10 participants. During this stage, the interval training had a slower progression towards 90% of MHR_{max}, and the protocol was stopped when the athlete reached 90% of MHR_{max} to immediately assess FHR and uteroplacental blood flow. As there were no indications of adverse events, we continued with the aforementioned protocol.

Patient and public involvement

This research was planned independently of direct patient (athlete) involvement. However, the medical team at the Norwegian Olympic Sports Centre provided valuable input on the study design, ensuring it aligned with practical and clinical relevance.

Statistical analyses

All statistical analyses were conducted using SPSS Statistical Software v. 28 (IBM, Armonk, New York, USA). Descriptive statistics are presented as mean with SD or frequencies with percentage, as appropriate. To compare MHR and FHR during running and cycling, paired samples t-tests were used. The association between the percentage of estimated MHR_{max} and FHR during running and cycling is illustrated using scatter plots. Due to the small number of fetal bradycardias, conducting any statistically significant testing between the groups was not feasible. Therefore, these results are presented descriptively without any statistical inferences. Uterine artery PI is the mean of measurements on both sides.

RESULTS

Participants

60 athletes, 10 elite athletes and 50 recreational athletes, participated in the study. The elite athlete group had five endurance athletes, four ball sport athletes and one CrossFit athlete. Among the recreational athletes, the majority engaged in strength training (n=41), running (n=39), cycling (n=20), CrossFit (n=13) and X-country skiing (n=12). Maternal age ranged from 24 to 44 years, and weekly exercise duration ranged from 4 to 17 hours, which was higher in the elite group than in the recreational athlete group (table 1). Most athletes were college or university-educated (n=57) and married or partnered (n=58). There were more primiparous (n=42) than multiparous (n=18) athletes.

Exercise measures

Four participants, three elite athletes and one recreational athlete, could not proceed with the treadmill running due to pelvic girdle pain identified during the pre-protocol checks. Three participants (one elite and two recreational athletes) did not complete the cycling due to time restraints (n=1), illness (n=1) or termination

Table 1 Participant characteristics. Results are presented as mean with SD and range (n=60).

	Mean (SD)	Range
Age (years)	31.9 (3.4)	24–44
Weight (kg)	73.7 (7.8)	58.9–100.6
Gestational age at testing (weeks)	29.3 (2.8)	25–36
Pre-pregnancy BMI, kg/m^2	22.4 (2.1)	18.8–28.3
Exercise hours/week	7.1 (3.2)	4–17
Elite athletes (n=10)	11.6 (3.2)	7–17
Recreational athletes (n=50)	7.0 (2.4)	4–17
Parity	0.3 (0.6)	0–2

BMI, body mass index.

of exercise due to prolonged fetal tachycardia after running (n=1). Therefore, 56 athletes completed baseline measures before running and 57 before cycling. Of these, 37 completed all five running intervals, and 51 completed all five cycling intervals (table 2). Reasons for not completing all running intervals included fetal bradycardia (n=6), fetal tachycardia (n=3), pelvic girdle pain that intensified after the third interval (n=1) and fatigue (n=1). Among the ten in the pilot group, eight were stopped from further exercise after reaching the intensity target to allow for immediate assessment of fetal well-being. Equally, the reasons for not completing all cycling intervals were abnormal fetal responses (n=4) and reaching the intensity target in the pilot group (n=2).

Mean RPE increased slightly across intervals but was not significantly higher during running than cycling. MHR increased steadily across intervals and was higher during running than cycling throughout all intervals (interval one: mean difference: 14.3 bpm (95% CI 11.5 to 17.0); interval two: mean difference: 10.7 bpm (9.2 to 13.0); interval three: mean difference: 9.2 bpm (7.2 to 11.2); interval four: mean difference: 7.9 bpm (6.0 to 9.7); interval five: mean difference: 6.3 bpm (4.5 to 8.0); all $p<0.001$) (table 2).

Table 3 presents the number of women (excluding the pilot group) who reached specific RPE and MHR_{max} thresholds across intervals. During running, 12 women reached ≥17 RPE for one interval, 3 for two intervals, 7 for three, 13 for four, and 8 for all five intervals. Regarding ≥90% of MHR_{max}, 4 reached this threshold for one interval, 4 for two, 6 for three, 5 for four and 13 for all five intervals. During cycling, 2 women reached ≥17 RPE for one interval, 10 for two, 12 for three, 14 for four and 4 for all five intervals. For ≥90% of MHR_{max}, 7 women reached

Table 2 Number of participants, maternal heart rate (MHR), percentage of estimated maximal MHR, and Borg's rating of perceived exertion (RPE), fetal heart rate (FHR) and umbilical and uterine artery pulsatile index (PI) for running and cycling, respectively. Results are presented as means with SD.

	Baseline	*Interval 1*	*Interval 2*	*Interval 3*	*Interval 4*	*Interval 5*
Running						
n	56	56	51	48	42	37
RPE		15.8 (1.6)	16.3 (1.3)	16.6 (0.8)	16.8 (0.7)	16.8 (0.5)
MHR		171.9 (9.4)	174.9 (8.2)	177.0 (7.5)	177.8 (7.4)	178.5 (8.2)
MHR%		87.5 (4.8)	89.1 (4.2)	90.1 (3.8)	90.5 (3.8)	90.9 (4.2)
FHR	140.1 (8.4)	140.3 (29.3)	143.7 (29.2)	147.4 (23.2)	152.7 (23.3)	145.2 (26.4)
Umbilical artery PI	1.0 (0.2)	0.9 (0.2)*	0.9 (0.2)	0.9 (0.2)*	0.9 (0.2)	1.0 (0.2)
Uterine artery PI	0.7 (0.2)†	0.8 (0.2)	0.7 (0.2)‡	0.7 (0.2)§	0.7 (0.3)¶	0.7 (0.2)**
Cycling						
n	57	57	57	57	55	51
RPE		14.9 (1.7)	15.8 (1.4)	16.3 (1.1)	16.6 (0.9)	16.9 (0.8)
MHR		156.7 (13.9)	163.5 (12.1)	167.6 (9.9)	170.0 (8.6)	172.6 (8.3)
MHR%		79.8 (7.1)	83.3 (6.2)	85.4 (5.0)	86.6 (4.3)	87.9 (4.2)
FHR	140.8 (9.2)	146.2 (17.2)	152.1 (17.5)	151.8 (17.5)	149.8 (24.2)	144.7 (23.5)
Umbilical artery PI	1.0 (0.2)	1.0 (0.2)**	0.9 (0.2)	0.9 (0.2)	0.9 (0.2)	1.0 (0.3)**
Uterine artery PI	0.7 (0.2)	0.7 (0.2)*	0.7 (0.2)‡	0.7 (0.2)‡	0.7 (0.3)††	0.7 (0.2)**

*Missing values for two athletes
†Missing values for eleven athletes
‡Missing values for five athletes
§Missing values for nine athletes
¶Missing values for three athletes
**Missing value for one athlete
††Missing values for four athletes

Table 3 Number and percentage of participants (n (%)) who reached specific thresholds of rating of perceived exertion (RPE) and maximal heart rate (MHR_{max}) during running and cycling. This data only includes participants who were not part of the pilot group.

	Interval 1	*Interval 2*	*Interval 3*	*Interval 4*	*Interval 5*
	n (%)	**n (%)**	**n (%)**	**n (%)**	**n (%)**
Running					
RPE≥16	39 (81.3)	40 (93.0)	39 (95.3)	36 (94.7)	36 (97.3)
RPE≥17	21 (43.8)	27 (62.8)	28 (68.3)	28 (73.7)	30 (81.2)
≥ 85% MHR_{max}	42 (87.5)	40 (93.0)	38 (92.7)	37 (97.4)	35 (94.6)
≥ 90% MHR_{max}	18 (37.5)	22 (51.2)	26 (63.4)	26 (68.4)	26 (70.3)
Cycling					
RPE≥16	26 (45.6)	37 (64.9)	44 (77.2)	48 (87.3)	48 (94.1)
RPE≥17	7 (12.3)	21 (36.8)	32 (56.1)	39 (70.9)	45 (88.2)
≥ 85% MHR_{max}	12 (21.1)	22 (38.6)	30 (52.6)	37 (67.3)	38 (74.5)
≥ 90% MHR_{max}	4 (7.0)	8 (14.0)	10 (17.5)	14 (25.5)	20 (39.2)

the threshold for one interval, 4 for two, 2 for three, 3 for four and 3 for all five intervals.

Fetal response to exercise

While mean FHR was slightly higher during cycling than running for most exercise intervals, the substantial variability in FHR prevented these differences from reaching statistical significance. Additionally, umbilical and uterine artery PI values remained within the normal range, with minimal changes observed throughout the intervals (table 2).

During running, mean FHR increased gradually from 140 bpm at baseline to 153 bpm after interval four and cycling from 141 bpm at baseline to 152 bpm after intervals two and three. There was, however, a large variation in FHR because of instances of fetal bradycardia and tachycardia. When analysing the data for running separately for participants with and without prolonged fetal bradycardia or tachycardia, those without (n=47) showed a mean increase in FHR of 6.9 bpm (from 139.6 bpm to 146.5 bpm; 95% CI: 1.8 to 12.1; p=0.009). In contrast, participants with fetal bradycardia (n=6) experienced a mean decrease in FHR of 65.0 bpm (from 144.3 bpm to 79.3 bpm; 95% CI: −85.6 to −44.5; p<0.001) and participants with fetal tachycardia (n=3) experienced a mean increase in FHR of 36.9 bpm (from 140.0 bpm to 176.9 bpm; 95% CI: 32.8 to 41.0; p<0.001). During cycling, there was a mean increase in FHR of 7.6 bpm (from 140.5 bpm to 148.1 bpm; 95% CI: 3.5 to 11.7; p<0.001) for those without fetal tachycardia (n=55). Participants with fetal tachycardia (n=2) had a mean increase in FHR of 24.0 bpm (from 148.0 bpm to 172.0 bpm; 95% CI: −5.6 to 53.6; p=0.062).

Fetal well-being

In total, FHR of <110 bpm was observed in 25 instances immediately after one of the intervals (figure 1A), indicative of transient bradycardia. Of these, six were prolonged (>3 min). Four cases occurred after the first interval, while the two others occurred after intervals two and three. In these cases, five women rated their perceived exertion as 17/20 and one as 18/20 on Borg's RPE scale. One woman exercised at 86.4% of MHR_{max}, two at 89.0% of MHR_{max}, and three at or above 90.0% of MHR_{max}. The duration of prolonged bradycardic episodes ranged from 3:20 to 8:00 min (average 5:20) after termination of exercise. During cycling, 11 fetuses experienced bradycardia immediately following one of the intervals (figure 1B), none of which were prolonged. One participant was stopped from further exercise due to recurrent transient fetal bradycardia (<3 min), and another in the pilot group was stopped after interval four due to transient fetal bradycardia. FHR of >160 bpm, consistent with transient tachycardia, was common during both exercise modes, with 71 episodes during running and 69 episodes during cycling (figure 1A,B). Exercise was terminated for three women during running and two women during cycling due to prolonged fetal tachycardia.

For women who reached ≥17 RPE for four or five intervals, the mean FHR was 150.0 (SD 13.8) during running and 151.5 (SD 11.6) during cycling. During running, five fetuses had FHR of <110 bpm for less than 3 min, and one exceeded 180 bpm for less than 4 min. During cycling, FHR was <110 bpm for less than 3 min in one case, and in another, FHR was >180 bpm for less than 4 min. Among those who reached ≥90% of MHR_{max} for four or five intervals, the mean FHR was 145.1 (SD 17.7) during running and 154.0 (SD 18.5) during cycling. During running, six fetuses had FHR <110 bpm for less than 3 min, while two exceeded 180 bpm for less than 4 min. During cycling, one fetus had FHR <110 bpm for less than 3 min. There were no cases of prolonged bradycardia or tachycardia.

Characteristics of the athletes who experienced prolonged fetal bradycardia are compared with those

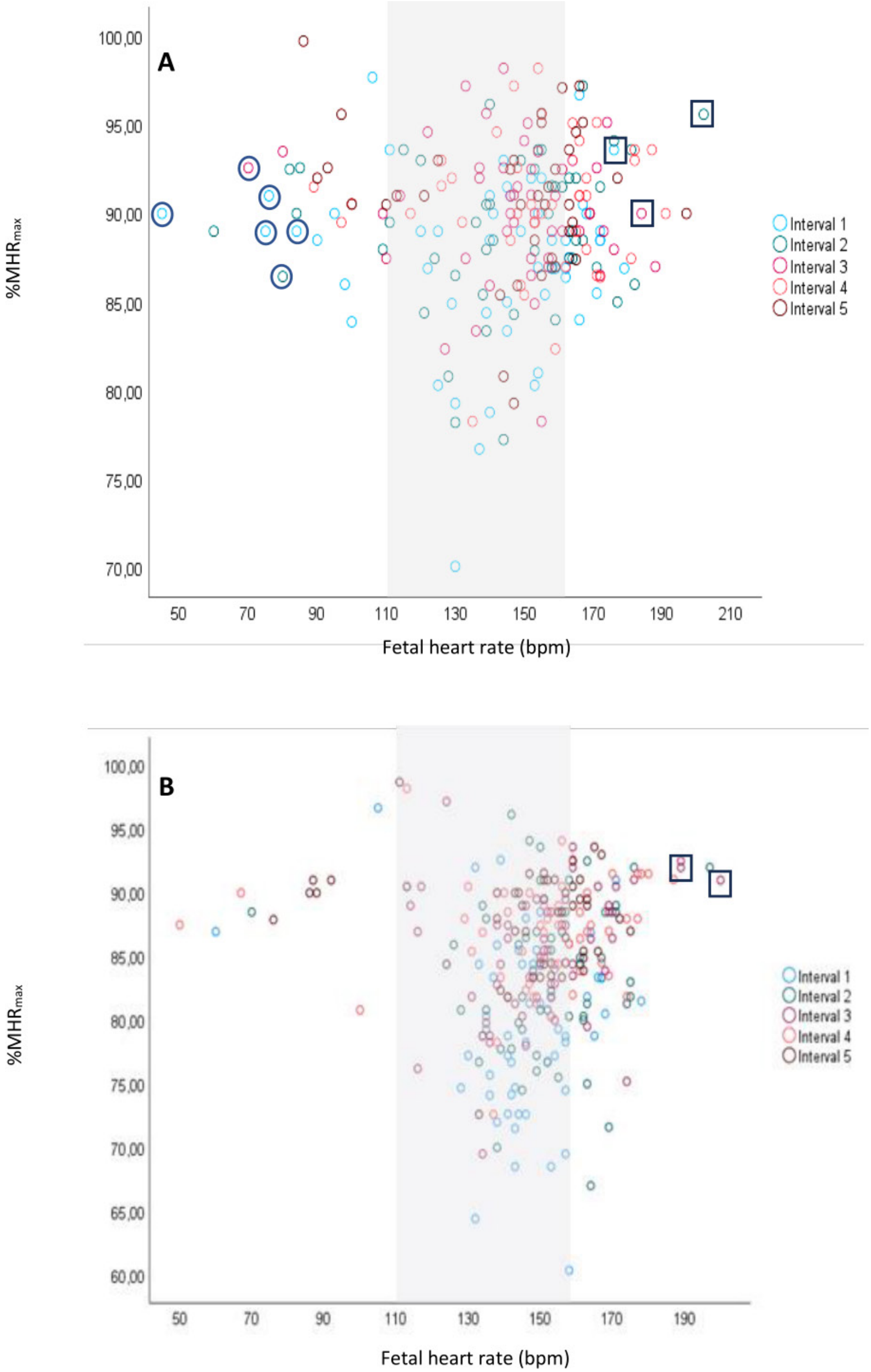

Figure 1 A and B: plot of percentage of estimated maximal maternal heart rate (%MHR_{max}) versus fetal heart rate (FHR) during running (A) and cycling (B). The grey area represents the normal FHR range (110-160 bpm). The large circles show cases of prolonged fetal bradycardia, and the squares show cases of prolonged fetal tachycardia.

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Table 4 Cases with and without bradycardia during treadmill running. All variables are presented as means with SD.

Variable	No bradycardia n=50	Bradycardia n=6
Gestational age (weeks)	28.9 (2.6)	30.0 (2.7)
Maternal age (years)	32.0 (3.6)	31.8 (1.5)
Exercise hours/week	7.2 (3.4)	6.3 (1.8)
Peak maternal heart rate (MHR)	178.9 (7.3)	176.0 (4.1)
Percentage of predicted MHR_{max} at peak	91.1 (3.7)	89.7 (2.1)
Fetal heart rate		
Baseline	139.6 (8.6)	144.3 (4.8)
Exercise*	148.4 (16.8)	79.3 (20.2)
Umbilical artery PI		
Baseline	1.0 (0.2)	1.0 (0.1)
Exercise*	0.9 (0.1)	1.2 (0.4) †
Uterine artery PI		
Baseline	0.7 (0.2)	0.7 (0.2)
Exercise*	0.7 (0.2) ‡	0.8 (0.2) §

*Mean of values from all five intervals.
†Missing value for one athlete
‡Missing values for two athletes
§Missing values for three athletes
MHR, Maternal heart rate; PI, pulsatility index.

Table 5 Fetal parameters at baseline and during running for cases with bradycardia

	Baseline	Interval 1	Interval 2	Interval 3	10–30 min rest
FHR (bpm)					
1	150	162	85	70	146
2	147	100*	80		152
3	145	45			149
4	142	76			138
5	146	75			†
6	136	84			135
Umbilical artery PI					
1	0.89	0.76	0.93	†	1.04
2	1.08	1.10	1.15		0.92
3	1.08	†			0.96
4	1.29	1.87			1.29
5	0.98	1.20			†
6	0.96	1.01			0.96
Uterine artery PI					
1	0.64	0.73	0.58	0.42	
2	0.98	1.05	1.00		
3	0.68	0.75			
4	0.68	†			
5	0.82	†			
6	0.52	†			

*Bradycardia <3 min
†Missing value
bpm, beats per minute; FHR, fetal heart rate; PI, pulsatility index.

who did not in table 4. Groups were similar across all parameters except for FHR during exercise (table 4).

Fetal parameters during running showed variability among cases with prolonged fetal bradycardia (table 5). Umbilical artery PI increased in most cases, though only one exceeded the 95th percentile.[18] All cases had normal Doppler waveforms, and after rest, PI values tended to decrease or return to baseline (table 5).

DISCUSSION

This study provides the largest evaluation of fetal responses to high-intensity exercise during pregnancy. We demonstrated that fetal well-being was not jeopardised following two bouts of high-intensity interval training in most athletes. However, prolonged fetal bradycardia and tachycardia were observed in some athletes, especially during treadmill running. Fetal tachycardia could be a protective mechanism that indicates compensation for hypoxaemia caused by reduced placental blood flow.[21] In contrast, fetal bradycardia may indicate a fetal cardiovascular response to increasing hypoxia but may also be a protective mechanism.[22]

Our results are consistent with previous studies of progressively increasing workloads (2 to 5 min stages) up to high intensity.[11 12] In the study by Szymanski and Satin,[12] five women in the highly active group experienced transient fetal bradycardia following a modified Balke treadmill protocol. The mean peak intensity was 95.9% (SD 5.3%) of predicted MHR_{max}. In the second study by Salvesen *et al*,[11] two of six elite athletes experienced transient fetal bradycardia when they exercised above 90% of MHR_{max}. The total exercise duration in both studies was between 20 and 25 min. Although fetal bradycardia can indicate fetal distress, the events identified in our study, as well as in the studies by Szymanski and Satin[12] and Salvesen *et al*,[11] were of short duration, not technically meeting the definition of sustained bradycardia, defined as FHR of <110 lasting 10 min or more,[23] thus suggesting limited clinical relevance.

Emerging evidence from two well-conducted studies showed no adverse fetal responses to short bursts (20–60 s) of near-maximal to maximal intensity exercise followed by 60 s of active recovery.[9 10] When considered alongside previous findings with high-intensity exercise of longer duration,[11 12] these results might suggest that high-intensity interval training of shorter duration carries a low risk of adverse fetal effects. This could be due to the shorter duration of stress on the maternal and fetal systems, allowing adequate recovery periods to mitigate potential risks.

Fetal bradycardia may be related to reduced uteroplacental blood flow.[11] In non-pregnant women, strenuous exercise is associated with an 88% redirection of blood flow to the working muscles.[24] This led to the hypothesis that acute exercise during pregnancy may transiently reduce uteroplacental blood flow, potentially causing fetal hypoxaemia and hypoxia and changes in FHR.[25] Salvesen *et al*[11] reported a reduction in uterine artery blood flow to approximately 40–75% of baseline values across all participants. However, a systematic review (with meta-analysis) showed that uterine and umbilical blood flow does not change during or after acute exercise,[26] which is consistent with our findings. Further, high umbilical artery PI,[18] indicating high blood flow resistance between the placenta and the fetus[26] was found in a previous study showing fetal bradycardia during high-intensity exercise.[11] On the other hand, Anderson *et al*[9] and Wowdzia *et al*[10] found decreases in mean umbilical artery indices from pre- to post-exercise, suggesting improved fetal-placental perfusion.[9] Although the numbers were small, we did observe increases in umbilical artery PI in most of the athletes in the prolonged bradycardia group following interval one, especially when there was also a notable decline in FHR. In most prolonged bradycardia cases, fetal perfusion improved or returned to baseline after rest.

In response to water submersion, the diving response is a protective mechanism in all mammals, including adult[27] and infant[28] humans. This multifaceted physiological reaction involves reflex bradycardia, apnoea and peripheral vasoconstriction.[27] The vasoconstriction is associated with a redistribution of blood flow, prioritising oxygen delivery to vital organs such as the brain and heart. Thus, the primary role of the diving response is to conserve oxygen and delay the onset of serious hypoxic damage.[27] During high-intensity maternal exercise, the fetus may activate its protective responses to counteract transient reductions in oxygen availability caused by maternal blood flow redistribution. Thus, the fetus may develop bradycardia and peripheral vasoconstriction, similar to the diving response, to preserve oxygen for essential organs. This hypothesis underscores the complex physiological adaptations in both adult and fetal systems to regulate oxygen availability under stress, and further research is needed to investigate the potential connection between fetal bradycardia and the diving response in humans.

Skow *et al*[26] found an increase in FHR of 6 bpm during acute maternal exercise, comparable to the fetal response in our study (average increase of 7 bpm among those without prolonged fetal bradycardia or tachycardia). In our study, measures of umbilical and uterine artery blood flow were unchanged with acute maternal exercise. Thus, the observed increase in FHR could be related to the release of maternal catecholamines, such as epinephrine and norepinephrine, during acute exercise.[29] Older reports have found that up to 15% of released catecholamines can cross the placenta and enter the fetal circulation.[30 31] This may induce changes in fetal movements, which, in turn, could lead to an increase in FHR.[30 31] Hence, the increased FHR during maternal exercise could be viewed as a normal fetal response to acute maternal exercise.

We observed no cases of prolonged fetal bradycardia during cycling. This is most likely due to the significantly higher MHR during running than cycling, particularly in intervals one, two and three, when prolonged fetal bradycardias occurred. Interestingly, no prolonged fetal bradycardias were observed after interval four or five, despite the exercise intensity being at its highest. This was also evident among those maintaining the target intensity for four or five intervals. Maternal adaptations may improve as the session progresses or the fetus adjusts to transient changes in oxygen supply and blood flow, reducing the likelihood of bradycardia despite the increasing intensity. Notably, both previous reports of fetal bradycardia during high-intensity exercise[11 12] involved weight-bearing exercises (treadmill running), whereas the studies reporting no adverse fetal effects[9 10] used non-weight-bearing exercises (resistance circuit and cycling, respectively). These studies also differ substantially in other key factors, including the duration of exercise intervals, the cumulative workload and maternal fitness levels, making direct comparisons challenging. Further research is needed to better understand the effects of exercise modality, duration and intensity on fetal well-being.

Clinical implications

Traditionally, high-intensity exercise in pregnancy has been discouraged due to concern for fetal well-being. Despite this, many women continue to engage in high-intensity exercise during pregnancy,[14] often facing uncertainty and anxiety due to limited information about safety issues.[14 32] In the current study, we demonstrate that high-intensity interval training was well tolerated by pregnant elite and recreational athletes, and the few cases of prolonged fetal bradycardia and tachycardia were normalised quickly. These findings are particularly important for athletes, coaches and healthcare providers navigating the challenges of developing safe training regimes for pregnancy. However, publicly available online information about high-intensity exercise during pregnancy fails to provide evidence-based guidance on exercise frequency, intensity and type, essential to ensure maternal and fetal safety.[14] Our findings will help to inform the development of evidence-based guidelines, but much more empirical research is needed.

Limitations

With a significantly larger number of participants, this study surpasses prior research[9–12] investigating high-intensity exercise during pregnancy. The protocol is based on the study by Salvesen *et al*.[11] Our study extends this foundational work by including a larger and more diverse group of pregnant women and incorporating both treadmill running and ergometer cycling. The inclusion of these two distinct training modes strengthens the study by providing a broader perspective on exercise intensity, offering valuable insights that can better inform future intensity recommendations for pregnant athletes.

Due to the limited knowledge of the safety of high-intensity exercise in pregnancy, the first 10 participants were used to pilot the study protocol, ensuring its feasibility and safety. Ultrasound measurements were conducted by an experienced OBGYN specialising in maternal-fetal medicine, ensuring both the validity of the data and the safety of the participants. The involvement of OBGYNs in data collection, particularly given the challenge of locating FHR via ultrasound post-exercise, was a significant strength of the study. Moreover, the prompt timing of data collection within minutes of exercise efforts enhanced the reliability of our measurements. In cases of abnormal findings, participants were referred to a hospital, prioritising maternal and fetal safety.

However, the study has some limitations. The study included more recreational than elite athletes, limiting the ability to compare these groups. Additionally, the exercise protocol included long passive pauses to accommodate ultrasound measurements, making it less reflective of a typical interval session. Some data were also missing, such as MHR at baseline and rest between intervals and uterine artery PI for participants with prolonged fetal bradycardia, as continuous monitoring of FHR was prioritised until normalisation. These missing data and the high variability of responses precluded any statistical inferences about the fetal responses to maternal exercise. Also, ultrasound measurements of fetal well-being could only be conducted before and immediately after exercise, as obtaining them during the activity is not feasible. Consequently, we cannot provide continuous information about fetal well-being throughout the exercise. Future research should include cardiotocography during exercise to gain detailed insights into FHR, including beat-to-beat variability and accelerations, while simultaneously allowing for the monitoring of uterine artery blood flow.

MHR_{max} was estimated based on an age-predicted formula.[9] While this provides the best available estimate of maximal intensity, it does not account for gestation-related physiological changes.[16] Since our participants took part in the study between gestational weeks 26 and 35, this limitation should be considered. Although RPE also presents challenges, such as individual differences in perception and potential intensity misclassification of intensity, it remains a well-established tool for assessing exertion.[16 17] Given the participants' training backgrounds and familiarity with how they respond to exercise at various intensities, RPE was likely a suitable and consistent measure of intensity in this group.

The study evaluated fetal responses to only two bouts of high-intensity interval training. While all participants delivered healthy offspring,[33] a single session cannot predict the cumulative effects of repeated sessions on maternal and fetal well-being. Prolonged reductions in oxygen transfer could theoretically increase risks, such as fetal growth restriction, although this was not observed in the Strong Mama project.

Furthermore, the findings are limited to healthy, highly active women with uncomplicated pregnancies, most of whom lived in Oslo, Norway. Therefore, these results may not be generalisable to all pregnant individuals. Further research is needed to evaluate the safety of high-intensity exercise in more diverse groups, including sedentary and obese women. High-intensity interval training is often considered more favourable than moderate-intensity training[9 10] because it overcomes the common barrier of limited time and has the potential to maintain or improve fitness levels.[34] Thus, it may provide additional benefits for less well-trained women.

The study also faced some technical limitations. Identifying and accurately measuring blood flow in the uterine arteries proved challenging due to the participants' elevated respiratory and heart rates. Additionally, many athletes had more collateral blood vessels than expected, making identifying the correct vessels for the PI measures difficult. In clinical settings, standard measurements are typically performed at rest, with the individual lying completely still, which contrasts with the dynamic conditions of this study. Unfortunately, MHR was not recorded at rest or between intervals, which restricted the ability to calculate proportional changes in maternal-fetal blood flow from rest to exercise and recovery. Lastly, all participants performed the exercises similarly; a randomised cross-over design could have provided more robust comparisons.

CONCLUSIONS

This study represents the largest evaluation of fetal responses to high-intensity exercise during pregnancy and provides valuable safety data for highly active women. Despite some athletes experiencing prolonged fetal bradycardia or tachycardia, our findings support that pregnant athletes can engage in acute bouts of high-intensity interval training without jeopardising fetal well-being. Further research is needed to confirm these findings across broader populations and explore the cumulative effects of repeated high-intensity exercise sessions.

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Contributors LAAH, KB, WB, BS, EMD, SB-P and KØ developed the study design and research questions. EMD (guarantor) was responsible for the recruitment and data collection, conducted analysis and led manuscript writing. BS, KØ and SB-P contributed to the collection of data. All authors contributed feedback on the full draft and provided approval before submission. ChatGPT was used to improve the language in some sections of the manuscript.

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Patient consent for publication Obtained.

Ethics approval This study involves human participants and was approved by Regional Committee for Medical and Health Research Ethics (REK 478976) and the Norwegian Agency for Shared Services in Education and Research (formerly known as Norwegian Social Science Data Service, NSD 628051). Participants gave informed consent to participate in the study before taking part.

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