

Dose-response relationship between evening exercise and sleep.

Leota et al. (2025)

Supplemental content.

Table S1. Participant Characteristics		
Variable	Mean $\pm$ SD	No. (%)
Total		14,689 (100)
Gender		
Women		3,844 (26.17)
Men		10,845 (73.83)
Age, y	37.89 $\pm$ 10.81	
18-44		10,837 (73.78)
44-64		3,555 (24.20)
64-87		297 (2.02)
Weight, KG	80.39 $\pm$ 15.10	
Height, CM	176.39 $\pm$ 9.41	
Cardiovascular indices		
Resting heart rate	56.41 $\pm$ 7.16	
HRV	59.95 $\pm$ 27.31	
Exercise information		
Exercises logged in analysis window	122.98 $\pm$ 53.74	
Exercise duration, mins	68.29 $\pm$ 55.27	

Table S2. Sleep Onset Estimated Marginal Means for Outcome Variables at Different Levels of Exercise Timing and Strain.

	Exercise Timing Relative to Habitual Sleep Onset						
Strain	-10 h	-8 h	-6 h	-4 h	-2 h	0	+2 h
None	23:06 (0.76)						
Light	23:09 (0.87)	23:07 (0.79)	23:04 (0.79)	23:01 (0.78)	23:10 (0.81)	00:05 (1.06)	02:39 (3.82)
Moderate	23:09 (0.90)	23:07 (0.80)	23:06 (0.79)	23:04 (0.79)	23:21 (0.83)	00:38 (1.17)	02:47 (3.92)
High	23:03 (1.03)	23:04 (0.83)	23:06 (0.84)	23:10 (0.83)	23:31 (0.89)	00:45 (1.38)	03:03 (5.06)
Maximal	22:57 (1.61)	23:00 (1.03)	23:03 (1.12)	23:18 (1.27)	23:46 (1.65)	01:09 (3.41)	03:49 (10.72)

Note. Values represent estimated marginal means for sleep onset (in 24 h clock time) with standard errors (in minutes) in parentheses.

Table S3. Sleep Duration Estimated Marginal Means for Outcome Variables at Different Levels of Exercise Timing and Strain.

	Exercise Timing Relative to Habitual Sleep Onset						
Strain	-10 h	-8 h	-6 h	-4 h	-2 h	0	+2 h
None	6.93 (0.51)						
Light	6.94 (0.67)	6.95 (0.55)	6.94 (0.55)	6.91 (0.54)	6.79 (0.58)	6.29 (0.88)	5.11 (3.60)
Moderate	6.94 (0.70)	6.96 (0.56)	6.93 (0.56)	6.87 (0.55)	6.68 (0.60)	5.94 (0.99)	4.79 (3.67)
High	6.99 (0.86)	6.98 (0.61)	6.94 (0.62)	6.85 (0.60)	6.58 (0.68)	5.81 (1.20)	4.56 (4.62)
Maximal	7.07 (1.46)	7.02 (0.84)	6.93 (0.94)	6.76 (1.08)	6.42 (1.46)	5.61 (2.90)	4.40 (8.64)

Note. Values represent estimated marginal means for sleep duration (in hours) with standard errors (in minutes) in parentheses.

Table S4. Sleep Quality Estimated Marginal Means for Outcome Variables at Different Levels of Exercise Timing and Strain.

	Exercise Timing Relative to Habitual Sleep Onset						
Strain	-10 h	-8 h	-6 h	-4 h	-2 h	0	+2 h
None	88.64 (0.05)						
Light	88.60 (0.05)	88.62 (0.05)	88.67 (0.05)	88.75 (0.05)	88.81 (0.05)	88.83 (0.06)	88.80 (0.09)
Moderate	88.55 (0.06)	88.59 (0.05)	88.62 (0.05)	88.65 (0.05)	88.73 (0.05)	88.47 (0.07)	87.84 (0.17)
High	88.49 (0.07)	88.50 (0.05)	88.43 (0.05)	88.53 (0.05)	88.55 (0.06)	88.08 (0.09)	85.95 (0.29)
Maximal	88.48 (0.11)	88.26 (0.07)	88.11 (0.07)	88.14 (0.08)	87.94 (0.11)	87.28 (0.22)	83.20 (0.67)
<i>Note.</i> Values represent estimated marginal means for sleep quality (%) with standard errors in parentheses.							

Table S5. Nocturnal RHR Estimated Marginal Means for Outcome Variables at Different Levels of Exercise Timing and Strain.

	Exercise Timing Relative to Habitual Sleep Onset						
Strain	-10 h	-8 h	-6 h	-4 h	-2 h	0	+2 h
None	56.33 (0.06)						
Light	56.82 (0.06)	56.80 (0.06)	56.73 (0.06)	56.66 (0.06)	56.78 (0.06)	58.35 (0.07)	62.83 (0.24)
Moderate	57.19 (0.07)	57.28 (0.06)	57.27 (0.06)	57.39 (0.06)	58.10 (0.06)	60.74 (0.08)	66.52 (0.25)
High	57.37 (0.07)	57.74 (0.06)	57.91 (0.06)	58.19 (0.06)	59.23 (0.07)	61.92 (0.09)	68.01 (0.31)
Maximal	58.25 (0.11)	58.83 (0.07)	59.14 (0.08)	59.53 (0.09)	60.66 (0.11)	63.72 (0.22)	72.26 (0.69)
<i>Note.</i> Values represent estimated marginal means for nocturnal RHR (beats/min) with standard errors are in parentheses.							

Table S6. Nocturnal HRV Estimated Marginal Means for Outcome Variables at Different Levels of Exercise Timing and Strain.

	Exercise Timing Relative to Habitual Sleep Onset						
Strain	-10 h	-8 h	-6 h	-4 h	-2 h	0	+2 h

None	60.20 (0.26)						
Light	58.64 (0.27)	58.66 (0.26)	59.02 (0.26)	59.36 (0.26)	59.02 (0.26)	55.65 (0.3)	44.95 (0.75)
Moderate	57.44 (0.28)	57.52 (0.26)	57.76 (0.26)	57.72 (0.26)	56.39 (0.27)	50.33 (0.31)	35.87 (0.79)
High	57.51 (0.29)	56.56 (0.27)	56.40 (0.27)	56.06 (0.27)	53.79 (0.27)	47.89 (0.34)	36.85 (0.94)
Maximal	55.68 (0.38)	54.61 (0.29)	54.45 (0.31)	53.29 (0.32)	50.72 (0.38)	43.63 (0.65)	30.29 (1.83)
<i>Note.</i> Values represent estimated marginal means for nocturnal HRV (RMSSD) with standard errors are in parentheses.							

Table S7. Sleep Onset Strain vs. No Exercise Contrasts for Outcome Variables at Different Levels of Exercise Timing and Strain.

	Exercise Timing Relative to Habitual Sleep Onset						
Contrast	-10 h	-8 h	-6 h	-4 h	-2 h	0	+2 h
Light – None	2.45 (0.43)	0.89 (0.22)	-2.24 (0.20)	-5.68 (0.19)	3.99 (0.27)	59.00 (0.73)	212.39 (3.74)
Mod. – None	2.36 (0.48)	1.31 (0.24)	-0.81 (0.23)	-2.03 (0.21)	15.14 (0.33)	91.83 (0.88)	220.97 (3.84)
High – None	-3.61 (0.70)	-1.59 (0.34)	-0.66 (0.35)	3.51 (0.32)	25.36 (0.46)	98.50 (1.15)	236.40 (5.00)
Maximal – None	-9.12 (1.42)	-5.90 (0.69)	-2.84 (0.82)	12.14 (1.01)	39.99 (1.46)	122.96 (3.32)	282.92 (10.69)

Note. Values represent sleep onset difference (minutes). Bolded values represent a significant change in the outcome variable from no exercise days ($p < .005$). Standard errors are in parentheses. Multivariate t-distribution adjustment method was used to adjust for multiple comparisons. Two-sided tests were used.

Table S8. Sleep Duration Strain vs. No Exercise Contrasts for Outcome Variables at Different Levels of Exercise Timing and Strain.

	Exercise Timing Relative to Habitual Sleep Onset						
Contrast	-10 h	-8 h	-6 h	-4 h	-2 h	0	+2 h
Light – None	0.38 (0.43)	1.07 (0.22)	0.92 (0.20)	-1.00 (0.18)	-8.35 (0.27)	-38.42 (0.71)	-109.37 (3.57)
Mod. – None	0.36 (0.48)	1.60 (0.24)	0.21 (0.23)	-3.35 (0.21)	-15.03 (0.33)	-59.58 (0.85)	-128.27 (3.64)
High – None	3.52 (0.69)	3.23 (0.34)	0.69 (0.35)	-4.75 (0.32)	-20.69 (0.46)	-67.18 (1.09)	-142.22 (4.59)
Maximal – None	8.50 (1.37)	5.41 (0.67)	0.28 (0.79)	-10.43 (0.95)	-30.62 (1.37)	-79.20 (2.86)	-151.62 (8.63)

Note. Values represent sleep duration difference (minutes). Bolded values represent a significant change in the outcome variable from no exercise days ($p < .005$). Standard errors are in parentheses. Multivariate t-distribution adjustment method was used to adjust for multiple comparisons. Two-sided tests were used.

Table S9. Sleep Quality Strain vs. No Exercise Contrasts for Outcome Variables at Different Levels of Exercise Timing and Strain.

	Exercise Timing Relative to Habitual Sleep Onset						
Contrast	-10 h	-8 h	-6 h	-4 h	-2 h	0	+2 h
Light – None	-0.04 (0.02)	-0.03 (0.01)	0.03 (0.01)	0.10 (0.01)	0.17 (0.01)	0.18 (0.03)	0.16 (0.08)
Mod. – None	-0.09 (0.03)	-0.05 (0.02)	-0.03 (0.01)	0.01 (0.01)	0.08 (0.02)	-0.17 (0.05)	-0.80 (0.16)
High – None	-0.15 (0.05)	-0.14 (0.02)	-0.21 (0.02)	-0.12 (0.02)	-0.09 (0.03)	-0.56 (0.07)	-2.70 (0.29)
Maximal – None	-0.16 (0.10)	-0.39 (0.05)	-0.53 (0.06)	-0.51 (0.07)	-0.70 (0.10)	-1.37 (0.21)	-5.44 (0.67)

Note. Values represent sleep quality difference (%). Bolded values represent a significant change in the outcome variable from no exercise days ($p < .005$). Standard errors are in parentheses. Multivariate t-distribution adjustment method was used to adjust for multiple comparisons. Two-sided tests were used.

Table S10. Nocturnal RHR Strain vs. No Exercise Contrasts for Outcome Variables at Different Levels of Exercise Timing and Strain.

	Exercise Timing Relative to Habitual Sleep Onset						
Contrast	-10 h	-8 h	-6 h	-4 h	-2 h	0	+2 h
Light – None	0.49 (0.03)	0.47 (0.01)	0.40 (0.01)	0.33 (0.01)	0.45 (0.02)	2.02 (0.05)	6.50 (0.23)
Mod. – None	0.86 (0.03)	0.95 (0.02)	0.94 (0.01)	1.06 (0.01)	1.76 (0.02)	4.41 (0.06)	10.19 (0.24)
High – None	1.04 (0.04)	1.41 (0.02)	1.58 (0.02)	1.86 (0.02)	2.90 (0.03)	5.59 (0.07)	11.68 (0.31)
Maximal – None	1.92 (0.09)	2.50 (0.04)	2.81 (0.05)	3.20 (0.06)	4.33 (0.09)	7.39 (0.21)	15.93 (0.68)

Note. Values represent nocturnal RHR difference (beats/min). Bolded values represent a significant change in the outcome variable from no exercise days ($p < .005$). Standard errors are in parentheses. Multivariate t-distribution adjustment method was used to adjust for multiple comparisons. Two-sided tests were used.

Table S11. Nocturnal HRV Strain vs. No Exercise Contrasts for Outcome Variables at Different Levels of Exercise Timing and Strain.

	Exercise Timing Relative to Habitual Sleep Onset						
Contrast	-10 h	-8 h	-6 h	-4 h	-2 h	0	+2 h
Light – None	-1.56 (0.09)	-1.54 (0.04)	-1.18 (0.04)	-0.84 (0.04)	-1.18 (0.05)	-4.55 (0.14)	-15.25 (0.71)
Mod. – None	-2.76 (0.10)	-2.68 (0.05)	-2.44 (0.05)	-2.48 (0.04)	-3.81 (0.07)	-9.87 (0.17)	-24.33 (0.74)
High – None	-2.69 (0.14)	-3.64 (0.07)	-3.80 (0.07)	-4.14 (0.06)	-6.41 (0.09)	-12.31 (0.22)	-23.35 (0.91)
Maximal – None	-4.52 (0.28)	-5.59 (0.14)	-5.75 (0.16)	-6.91 (0.19)	-9.48 (0.28)	-16.57 (0.59)	-29.91 (1.81)

Note. Values represent nocturnal HRV difference (RMSSD). Bolded values represent a significant change in the outcome variable from no exercise days ($p < .005$). Standard errors are in parentheses. Multivariate t-distribution adjustment method was used to adjust for multiple comparisons. Two-sided tests were used.

Table S12. Demographic Characteristics of Individuals Included In (and Excluded From) The Final Sample

Group		Included		Excluded	
Variable		Mean $\pm$ SD	No. (%)	Mean $\pm$ SD	No. (%)
Total			14,689 (73.4)		5,311 (26.6)
Gender					
	Women		3,844 (26.17)		1,361 (25.6)
	Men		10,845 (73.83)		3,926 (73.9)
	NA				24 (0.5)
Age, y		37.89 $\pm$ 10.81		39.94 $\pm$ 10.41	
Weight, KG		80.39 $\pm$ 15.10		84.34 $\pm$ 18.80	
Height, CM		176.39 $\pm$ 9.41		176.39 $\pm$ 9.76	
Cardiovascular indices					
	Resting heart rate	56.41 $\pm$ 7.16		60.52 $\pm$ 7.97	
	HRV	59.95 $\pm$ 27.31		50.49 $\pm$ 23.62	

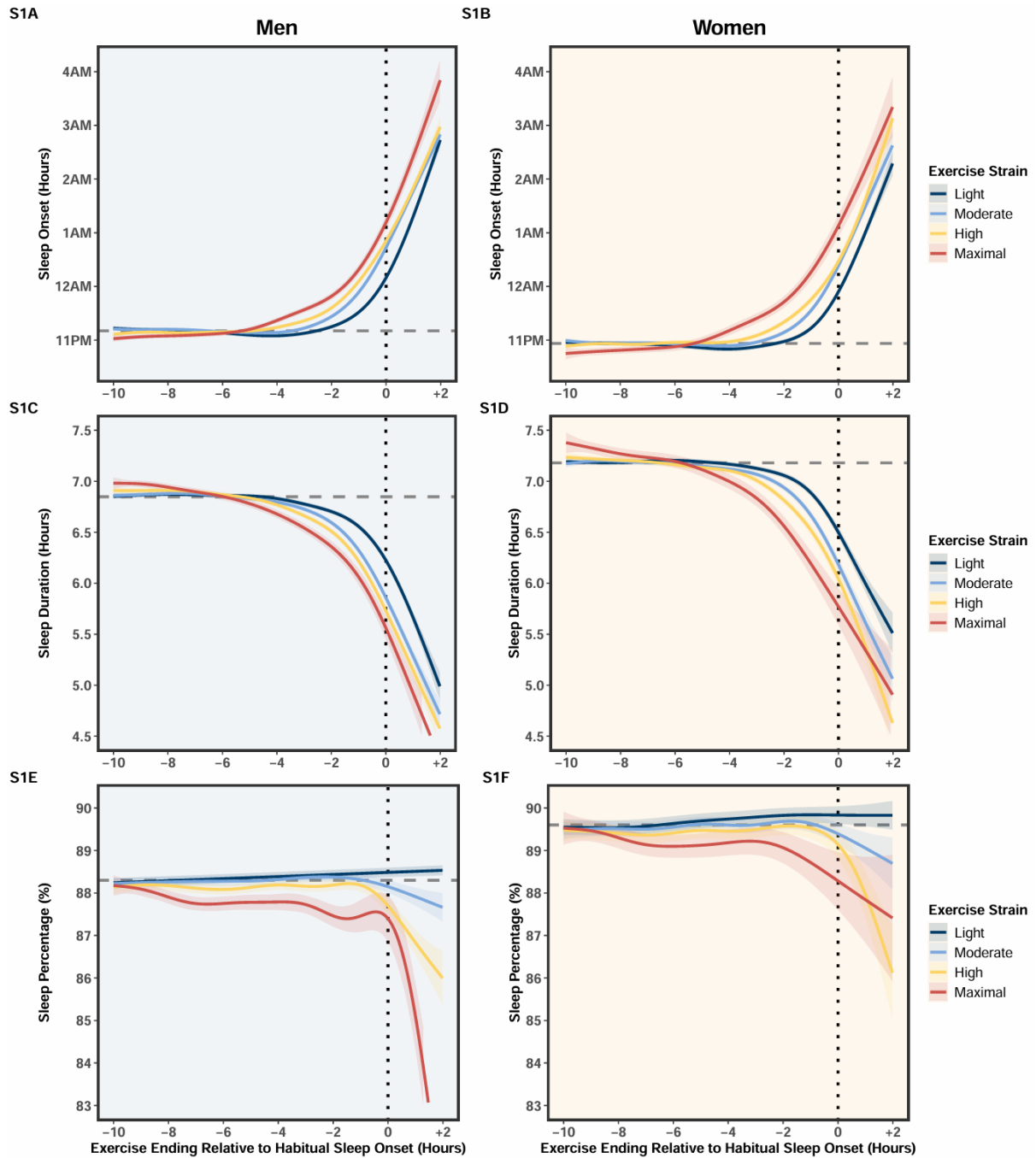


Figure S1. GAMMs demonstrating the relationship between exercise timing relative to habitual sleep onset and **A-B.** sleep onset, **C-D.** sleep duration (in hours), and **E-F.** sleep quality at different levels of exercise strain stratified by gender (men shaded in blue on the left; women shaded in cream on the right). Shaded area surrounding each exercise strain group line represents 95% confidence intervals. Horizontal grey dashed line indicates the mean outcome variable on no exercise days. Vertical black dotted line indicates habitual sleep onset.

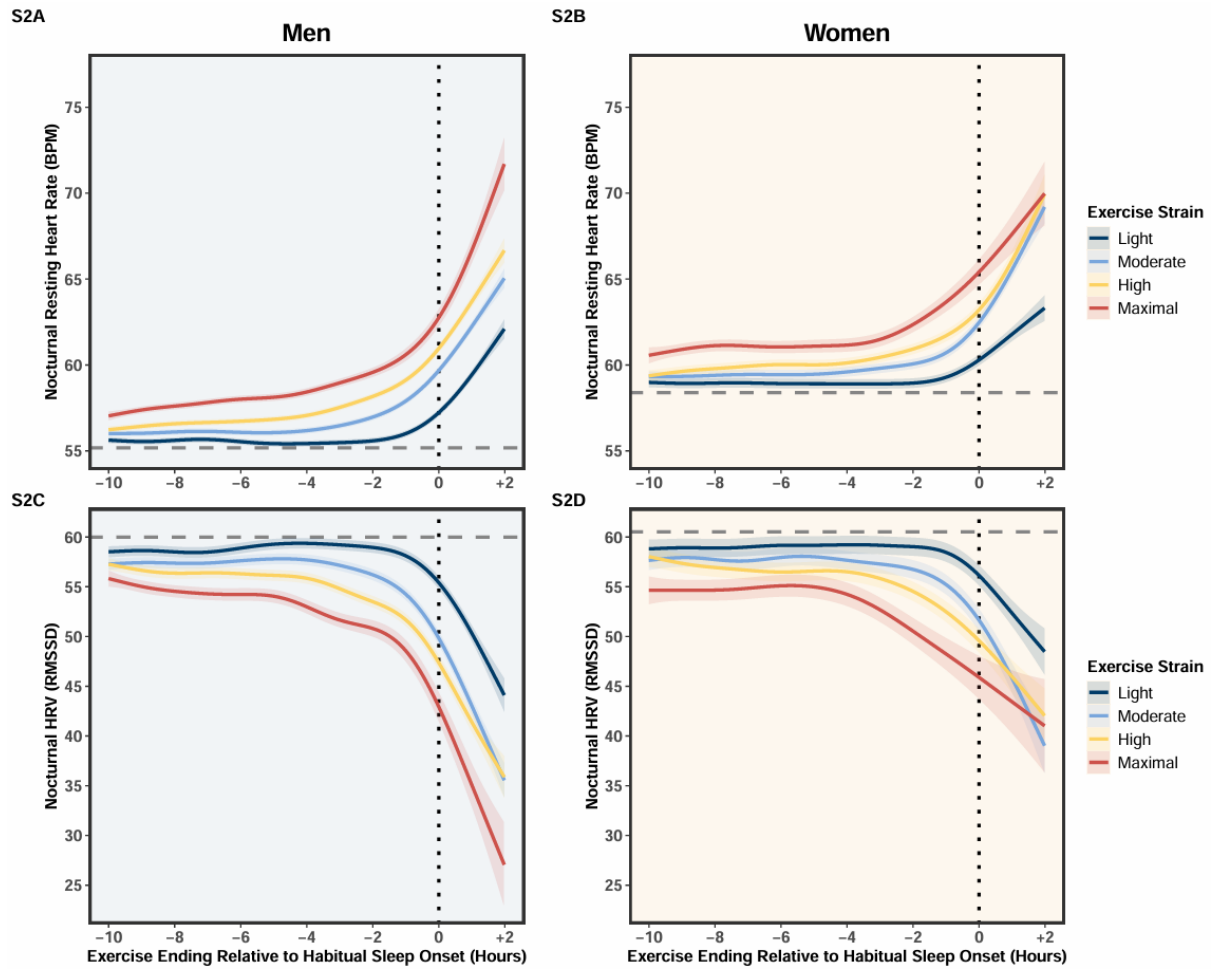


Figure S2. GAMMs demonstrating the relationship between exercise timing relative to habitual sleep onset and **A-B.** nocturnal resting heart rate, and **C-D.** nocturnal HRV at different levels of exercise strain stratified by gender (men shaded in blue on the left; women shaded in cream on the right). Shaded area surrounding each exercise strain group line represents 95% confidence intervals. Horizontal grey dashed line indicates the mean outcome variable on no exercise days. Vertical black dotted line indicates habitual sleep onset.

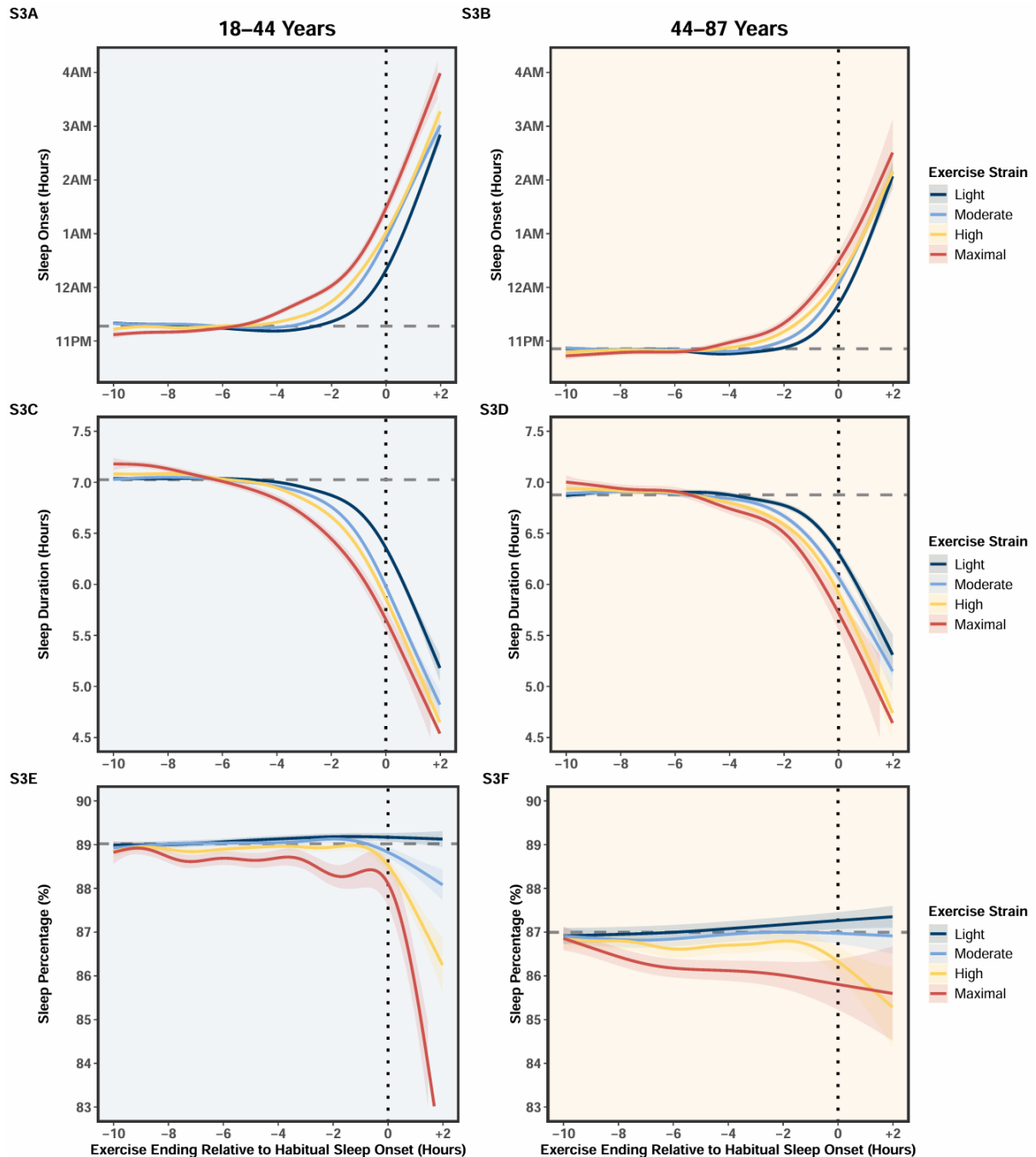


Figure S3. GAMMs demonstrating the relationship between exercise timing relative to habitual sleep onset and **A-B.** sleep onset, **C-D.** sleep duration (in hours), and **E-F.** sleep quality at different levels of exercise strain stratified by age (18–43 years of age shaded in blue on the left; 44–87 years of age shaded in cream on the right). Shaded area surrounding each exercise strain group line represents 95% confidence intervals. Horizontal grey dashed line indicates the mean outcome variable on no exercise days. Vertical black dotted line indicates habitual sleep onset.

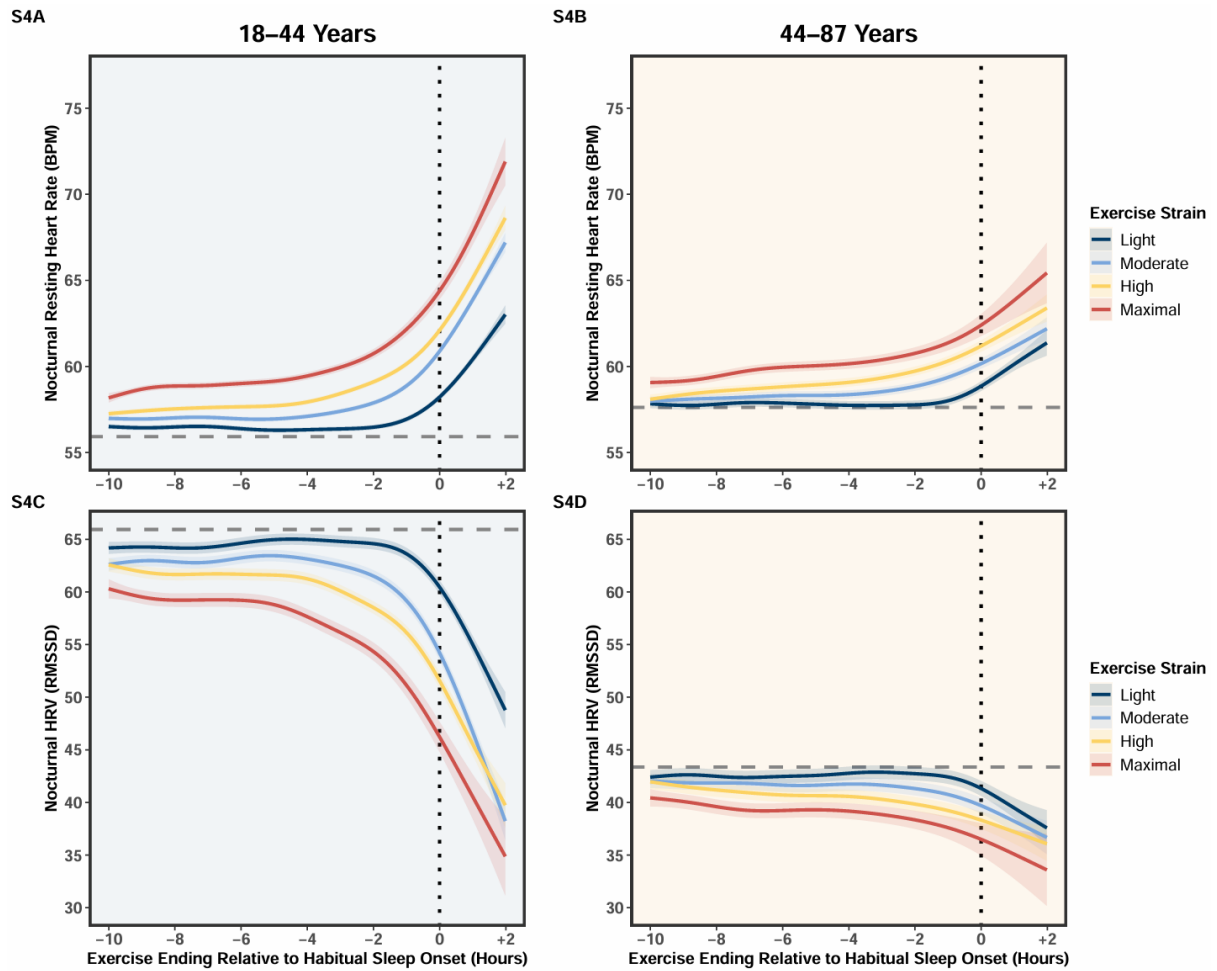


Figure S4. GAMMs demonstrating the relationship between exercise timing relative to habitual sleep onset and **A-B.** nocturnal resting heart rate, and **C-D.** nocturnal HRV at different levels of exercise strain stratified by age (18–43 years of age shaded in blue on the left; 44–87 years of age shaded in cream on the right). Shaded area surrounding each exercise strain group line represents 95% confidence intervals. Horizontal grey dashed line indicates the mean outcome variable on no exercise days. Vertical black dotted line indicates habitual sleep onset.

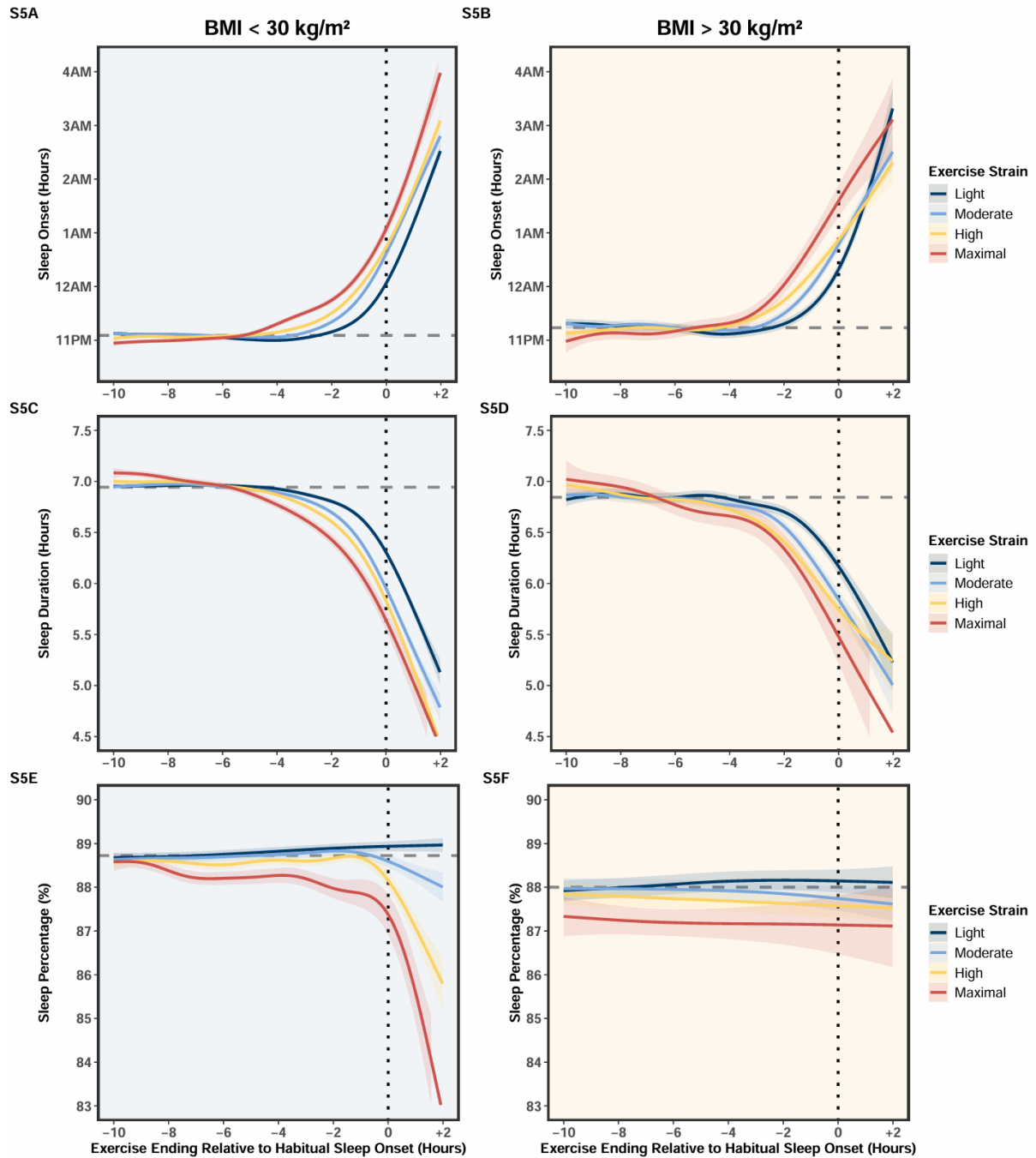


Figure S5. GAMMs demonstrating the relationship between exercise timing relative to habitual sleep onset and **A-B.** sleep onset, **C-D.** sleep duration (in hours), and **E-F.** sleep quality at different levels of exercise strain stratified by BMI status (BMI < 30 [kg/m²] shaded in blue on the left; BMI ≥ 30 [kg/m²] shaded in cream on the right). Shaded area surrounding each exercise strain group line represents 95% confidence intervals. Horizontal grey dashed line indicates the mean outcome variable on no exercise days. Vertical black dotted line indicates habitual sleep onset.

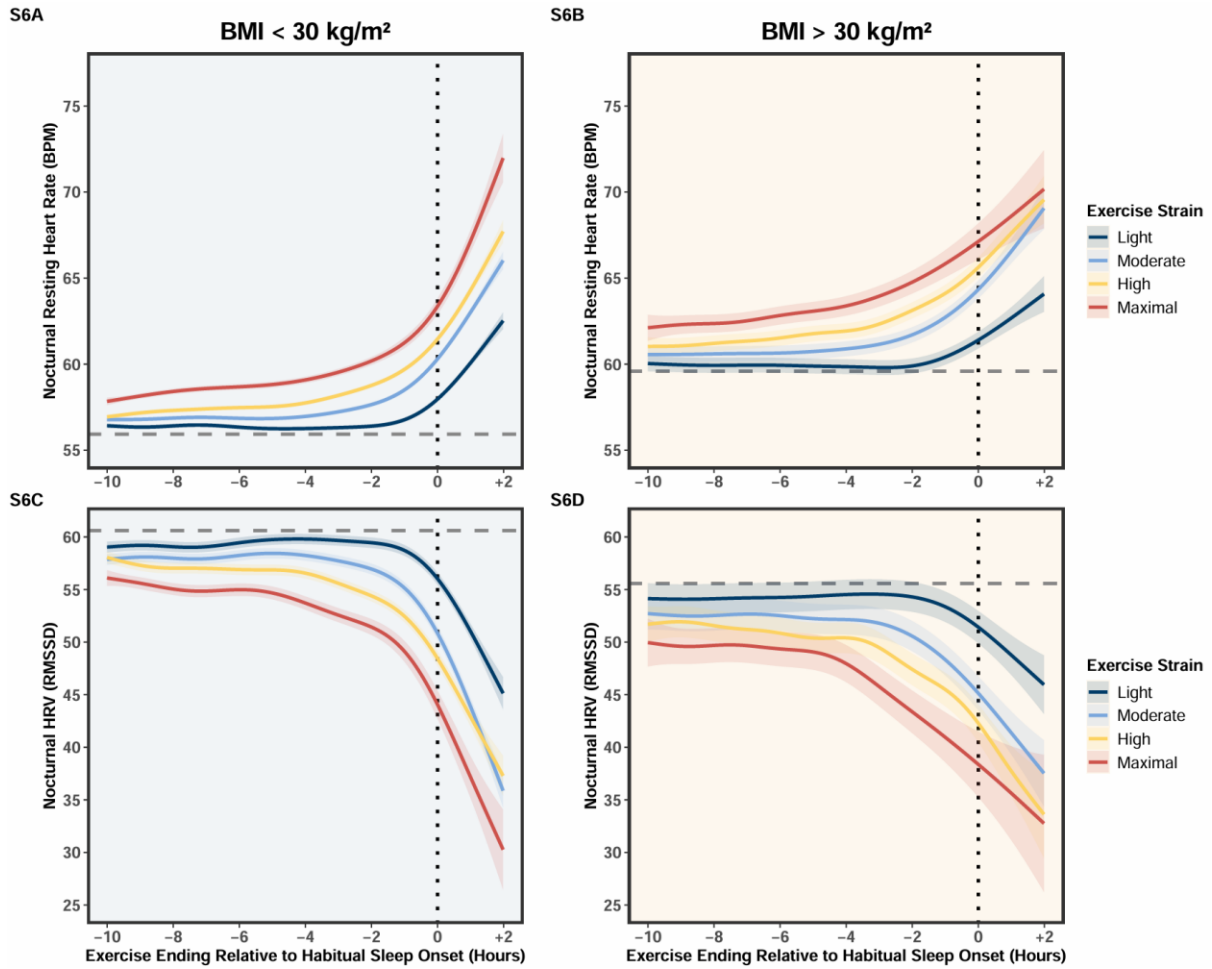


Figure S6. GAMMs demonstrating the relationship between exercise timing relative to habitual sleep onset and **A-B.** nocturnal resting heart rate, and **C-D.** nocturnal HRV at different levels of exercise strain stratified by BMI status (BMI < 30 [kg/m²] shaded in blue on the left; BMI ≥ 30 [kg/m²] shaded in cream on the right). Shaded area surrounding each exercise strain group line represents 95% confidence intervals. Horizontal grey dashed line indicates the mean outcome variable on no exercise days. Vertical black dotted line indicates habitual sleep onset.