论著·智能医学与预测模型

个人特质是影响人体热耐力的核心因素:基于健康生态学模型的多因素交互作用分析

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[摘要] **目的** 鉴于全球气候变暖导致人体高温暴露事件频发,本研究运用健康生态学模型,从个人特质、行为特征、环境适应行为与人际网络等多维度系统探究热耐力的影响因素及其交互作用路径与机制,以应对高温环境下的热损伤风险。**方法** 2024年8月21日至9月13日通过问卷星和微信平台对重庆市2 596名高校师生进行横断面调查,依据调查数据将热耐力划分为低、中、强3个等级,并运用χ^2检验、多项Logistic回归和结构方程模型,分析人口学特征和健康生态学各维度因素对热耐力的组间差异、独立影响及路径关系。**结果** 热耐力与社会人口学特征(性别、年龄、热浪经历)、个人特质、行为特征、环境适应行为(淋浴次数、外出戴帽)及人际网络(关注天气、中暑时及时求助)均存在组间差异(P<0.05)。其中女性达到中等热耐力[OR=0.496(95%CI:0.390~0.631)]和强热耐力[OR=0.250(95%CI:0.178~0.349)]的概率显著低于男性(P<0.001);并且16~18岁[OR=3.778(95%CI:2.028~7.039)]和19~21岁[OR=1.913(95%CI:1.021~3.586)]的群体比≥26岁的群体更有可能达到强热耐力(P<0.05),而未经历热浪者达到强热耐力的概率显著降低[OR=0.475(95%CI:0.257~0.878),P<0.05]。结构方程模型进一步揭示这些因素的多路径交互作用。男性的热耐力优势不仅体现在生理上的直接效应(标准化路径系数为0.261),更通过提升个人特质间接发挥作用(标准化路径系数为0.185)。尽管年龄增长对热耐力有直接的负向影响(标准化路径系数为-0.067),但其对个人特质的提升(标准化路径系数为0.038)却能间接抵消这一不利效应。个人特质是影响热耐力的核心因素,其标准化路径系数高达0.696,远超其他因素,并作为关键的中介变量调节性别、年龄及行为特征对热耐力的整体影响。此外,尽管行为特征对热耐力的直接作用不显著(P=0.871),但其通过强化个人特质产生了显著的间接效应(标准化路径系数为0.304),而环境适应行为则呈现出负向影响(标准化路径系数为-0.143),表明过度依赖环境适应可能抑制热耐力的发挥。**结论** 热耐力受多因素综合影响,其中个人特质是核心因素,对热耐力具有显著的直接与间接作用。提升个人特质是增强热耐力、降低热损伤风险的关键策略。

[关键词] 热耐力;健康生态学模型;行为特征;个人特质
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Personal traits as the core determinant of human heat tolerance: a multi-factorial interaction analysis based on the health ecological model

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[**Abstract**] Objective With the increasing frequency of human heat exposure events driven by

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global climate warming, this study employed the health ecological model to systematically investigate the influencing factors of heat tolerance and their interaction pathways and mechanisms across multiple dimensions including personal traits, behavioral characteristics, environmental adaptation behaviors, and interpersonal networks, aiming to address the risk of heat injury in high-temperature environments. **Methods** A cross-sectional survey was conducted on 2 596 university faculty and students in Chongqing from August 21 to September 13, 2024, *via* the Wenjuanxing and WeChat platforms. Based on the survey data, heat tolerance was classified into 3 levels (low, moderate, strong). *Chi*-square test, multinomial logistic regression, and structural equation modeling were applied to analyze group differences, independent effects, and path relationships of demographic characteristics and factors at each level of the health ecological model on heat tolerance. **Results** Heat tolerance exhibited group differences with sociodemographic characteristics (sex, age, heatwave experience), personal traits, behavioral characteristics, environmental adaptation behaviors (shower frequency, wearing hats outdoors), and interpersonal networks (weather monitoring, timely seeking help for heatstroke) ($P<0.05$). Specifically, females demonstrated significantly lower probabilities of achieving moderate heat tolerance (*OR*=0.496, 95%*CI*: 0.390 to 0.631) and strong heat tolerance (*OR*=0.250, 95%*CI*: 0.178 to 0.349) compared to males ($P<0.001$). The participants aged 16 to 18 years (*OR*=3.778, 95%*CI*: 2.028 to 7.039) and 19 to 21 years (*OR*=1.913, 95%*CI*: 1.021 to 3.586) were more likely to attain strong heat tolerance than those aged ≥26 years ($P<0.05$), and those without heatwave experience showed significantly reduced probability of achieving strong heat tolerance (*OR*=0.475, 95%*CI*: 0.257 to 0.878, $P<0.05$). Structural equation modeling further revealed the multipath interactions among these factors. The male advantage in heat tolerance was manifested not only through direct physiological effects (standardized path coefficient=0.261) but also indirectly *via* enhancement of personal traits (standardized path coefficient=0.185). Although increasing age exerted a direct negative effect on heat tolerance (standardized path coefficient=−0.067), its promotion of personal traits (standardized path coefficient =0.038) indirectly offset this adverse effect. Personal traits emerged as the core determinant of heat tolerance, with a standardized path coefficient as high as 0.696, substantially exceeding all other factors, and serving as a critical mediating variable regulating the overall effects of sex, age, and behavioral characteristics on heat tolerance. Furthermore, although behavioral characteristics showed no significant direct effect on heat tolerance ($P=0.871$), they generated significant indirect effects through strengthening personal traits (standardized path coefficient=0.304), whereas environmental adaptation behaviors demonstrated a negative impact (standardized path coefficient=−0.143), suggesting that over-reliance on environmental adaptation may suppress the expression of heat tolerance. **Conclusion** Heat tolerance is influenced by multiple integrated factors, among which personal traits constitute the core determinant exerting significant direct and indirect effects on heat tolerance. Enhancing personal traits represents the key strategy for improving heat tolerance and reducing the risk of heat injury.

[**Key words**] heat tolerance; health ecological model; behavioral characteristics; personal traits

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热耐力是指从温暖到炎热条件下保持身体活动的能力[1]。热耐力差者生理应激指数高、热应激反应强、中暑风险高[2],是中暑发生的主要机制之一[3]。影响热耐力的因素众多,生理上取决于核心体温调控、心血管功能、汗腺反应;心理上看主观疲劳感与韧性动机;环境上由温度、湿度、热辐射和风速决定;训练上则依赖热习服程度、有氧能力及适应性等[4-6]。传统研究多聚焦单一层面因素,难以系统解析这些复杂因素的交互作用机制。为克服此局限,本研究引入健康生态学理论作为整合性分析框架。该理论将热耐力视为个人特质、行为特征、人际网络、环境适应行为等4个层面动态交互的结果[7]。该框架将热耐力从单一生理指标拓展为“个体-行为-社会-环境”多维建构的产物,打破了传统研究的局限,系统分析热耐力影响因素,为制定中暑防控策略提供了多层次、可量化的理论依据与数据支撑。

1 资料与方法

1.1 研究对象

本研究于2024年8月21日至9月13日期间,通过

问卷星、微信等平台向重庆市各高校师生匿名发放《热耐力人群特征调查问卷》。鉴于热暴露时长与劳动强度是影响热耐力的关键因素,本研究旨在建立“低热暴露-低体力负荷”人群的热耐力特征。纳入标准:①居住或近期在重庆市(高温易感地区)工作、生活的高校师生;②日常以脑力活动为主,无长期户外体力劳动或高强度体能训练经历;③自愿参与本研究并签署知情同意书。排除标准:①问卷信息填写不完整,关键条目缺失数量≥3项;②回答模式异常,存在明显的规律性作答、矛盾性作答;③未完成全部问卷作答、中途退出的样本。调查对象均知情同意,并获得陆军军医大学医学伦理委员会审批(2023第2-02)。

1.2 方法

1.2.1 样本量的估算 样本量确定应综合Logistic回归与结构方程模型要求。根据EPV法则[8](每个自变量对应的有效样本≥10),拟纳入25个自变量,需至少250例有效样本。预调查显示强热耐力约占总体的12.5%,为保证该等级的统计功效,总样本量需扩大至2 000例。结构方程模型的近似均方根误差(root mean square error of approximation, RMSEA)功效分析[9](df=70,α=0.05,Power=0.90)显示,检测RMSEA从0.08降至0.05所需样本量为215例。综合两种方法确定最终样本量为2 000例。

1.2.2 抽样方法 本研究为横断面研究,采用方便抽样选取受试者,共回收问卷2 695份,剔除32份关键信息缺失样本及67份逻辑不一致样本,最终获得有效样本2 596份,有效回收率达96.3%。

1.2.3 热耐力分级原则 热耐力分级,依据“高温高湿环境下您是否感到不适”与“您在高温天气下身体出现过哪些不适症状”2项结果,将受试者按热耐力分为3级:①强耐力,无主观不适且无客观症状(n=324);②中等耐力,否认主观不适但已出现隐性症状(n=546);③低耐力,既承认主观不适又伴随明确症状(n=1 726)。此分级构建了强耐力(无症状)—中等耐力(隐性症状)—低耐力(显性不适)的热耐力评价等级。

1.2.4 调查问卷设计 本研究以健康生态学模型为理论框架,将个人特质、行为特征、人际网络及环境适应行为作为影响热耐力的4个维度。问卷在参考2015年中国健康教育中心编制的《全国居民健康素养监测调查问卷》[10]和热习服研究常用条目[11]基础上,结合研究目标设计,主要包括以下内容。

个人特质维度包括基础疾病、健康感知和生理状态。基础疾病收集受试者是否被医院诊断过呼吸系统、心脑血管、过敏及其他疾病。健康感知从4个维度描述个体对自身健康状态的评估:“我好像比别人容易生病”衡量个体对自身免疫力的担忧,“我认为我的健康状况在变坏”衡量个体对健康变化趋势的担忧,此2题衡量被试者感知自身健康的脆弱性和不确定性,采用反向计分;“我跟我认识的人一样健康”和“我的健康状况非常好”评估个体在当前环境中对自身健康保持乐观的指标,采用正向计分;以上4题均采用4级评分,高分代表积极感知。生理状态包括食欲、睡眠质量、静息时乏力困倦3个题项,采用Likert 5级评定法,高分表示症状轻微。该维度量表信效度良好(Cronbach's α=0.815,KMO=0.856,Bartlett球形检验P<0.001)。

行为特征维度旨在测量与热耐力相关的健康行为。初始包含每日吸烟、每日饮水量、饮茶习惯、饮食偏好、每日睡眠时长、每月熬夜频率、每周健身次数、每次健身时长、健身项目共9个题项。其中每日吸烟与饮茶习惯采用二分类(是/否),其余均采用4级评分,得分越高代表行为越健康。因子分析适宜性检验表明数据适合进行因子分析(KMO=0.712,Bartlett球形检验χ^2=2 008.255,P<0.001)。主成分分析提取出2个因子,根据理论意义与信度标准,最终保留第一个因子,包含每日饮水量、每周健身次数、每次健身时长和健身项目4个题项(因子载荷0.511~0.777),其内部一致性可接受(Cronbach's α=0.669,各项题总相关>0.300)。

环境适应行为维度评估个体在高温环境下的主动适应策略。初始包含高温喝更多水、高温增加淋浴次数、高温换薄衣、高温打开空调风扇、高温外出戴帽等5个题项,选项从“从不”到“经常”,均采用4级评分,得分越高高温适应行为越好。因子分析适宜性检验支持因子分析(KMO=0.680,Bartlett球形检验χ^2=1 410.555,P<0.001)。主成分分析提取出2个因子,依据信效度指标,最终保留第一个因子,包含高温喝更多水、高温增加淋浴次数、高温换薄衣、高温打开空调风扇等4个题项(因子载荷0.650~0.808),其内部一致性尚可(Cronbach's α=0.610,各项题总相关>0.300)。

人际网络维度旨在考查社会支持与信息获取对热适应的影响。初始包括关注天气预报、关注健康指南、中暑时及时就医或求助等3个题项。然而,因子分析适宜性检验表明数据不适合进行因子分析(KMO=0.546),且量表内部一致性极低(Cronbach's α=0.397)。因此,该维度在本研究中未形成可靠测量,未纳入后续结构方程模型分析。

1.3 统计学分析

统计分析在SPSS 26.0与R软件中完成。计数资料以频数(%)描述;组间比较采用χ^2检验(理论频数<5时则用Fisher精确法)。多因素分析因经平行线检验不满足有序Logistic回归假设,遂采用多项Logistic回归,以向后步进法(纳入P<0.05、剔除P>0.10)筛选

变量,并监测方差膨胀因子(variance inflation factor,VIF,<5)控制共线性,模型显著且拟合良好。随后构建结构方程模型,因结局变量为有序分类数据且部分观测变量显著偏离正态分布,故采用加权最小二乘法进行分析,模型拟合度以拟合优度指数(goodness-of-fit index,GFI)、Tucker-Lewis指数(Tucker-Lewis index,TLI)、比较拟合指数(comparative fit index,CFI)、RMSEA及标准化均方根残差(standardized root mean square residual,SRMR)评估,达标标准:χ^2/df<3、GFI>0.90、TLI>0.90、CFI>0.90、RMSEA<0.08、SRMR<0.08,显著性水平α=0.05(双侧)。

2 结果

2.1 调查对象人口学特征及与热耐力的组间比较

本研究共调查了2 596名高校师生,其中男性占比33.8%,女性占比66.2%;年龄以22岁以下为主,占比85%;BMI介于正常范围(18.5~24.0 kg/m^2)的人数最多,占63.5%;以汉族为主,占比91.6%;文化程度以本科居多,占88%;籍贯以四川居多(占比约71.2%),94.6%都经历过热浪事件。χ^2检验显示:性别、年龄、经历热浪事件等3项在不同热耐力水平之间存在显著差异;详见表1。

2.2 热耐力与健康生态学各维度因素的组间比较

本研究对所有题项进行χ^2检验,结果显示,19个题项的得分在不同热耐力水平之间存在显著差异。具体包括:个人特质中的全部8个题项(表2);行为特征中的每日吸烟、每日饮水量、每日睡眠时长、每月熬夜频率、每周健身次数、每次健身时长及健身项目等7项(表3);环境适应行为中的高温增加淋浴次数、高温外出戴帽等2项(表4);人际网络中的关注天气预报、中暑时及时就医或求助等2项(表5)。

2.3 影响热耐力的关键因素:多项Logistic回归分析

2.3.1 多重共线性诊断 对22项有显著性影响的自变量进行哑变量处理后,开展多重共线性诊断,结

表1 社会人口学特征与热耐力的组间比较[例(%)]

Table 1 Social demographic characteristics and intergroup comparison of heat tolerance [n(%)]

Variable	Low heat tolerance(n=1 726)	Moderate heat tolerance(n=546)	Strong heat tolerance(n=324)	χ^2	P
Gender				229.983	<0.001
Male	428(48.8)	237(27.0)	212(24.2)		
Female	1 298(75.5)	309(18.0)	112(6.5)		
Age/years				26.834	<0.001
16 to 18	660(62.3)	241(22.8)	158(14.9)		
19 to 21	811(70.6)	231(20.1)	106(9.2)		
22 to 25	145(65.3)	40(18.0)	37(16.7)		
≥26	110(65.9)	34(20.4)	23(13.8)		
Body mass index				9.898	0.129
Underweight	370(68.8)	112(20.8)	56(10.4)		
Normal	1 106(67.1)	336(20.4)	207(12.6)		
Overweight	189(61.8)	69(22.5)	48(15.7)		
Obese	61(59.2)	29(28.2)	13(12.6)		
Ethnicity				1.181	0.554
Han	1 587(66.8)	494(20.8)	296(12.5)		
Ethnic minority	139(63.5)	52(23.7)	28(12.8)		
Place of birth				1.402	0.496
Southern China	1 546(66.2)	493(21.1)	297(12.7)		
Northern China	180(69.2)	53(20.4)	27(10.4)		
Education level				6.006	0.423
Secondary vocational education	111(68.9)	28(17.4)	22(13.7)		
Higher vocational education	21(60.0)	10(28.6)	4(11.4)		
Bachelor's degree	1 515(66.3)	490(21.5)	279(12.2)		
Master's degree	79(68.1)	18(15.5)	19(16.4)		
Experienced heatwave events				6.878	0.032
Yes	1 647(67.1)	509(20.7)	300(12.2)		
No	79(56.4)	37(26.4)	24(17.1)		

表2 个人特质与热耐力的组间比较[例(%)]

Table 2 Personal traits and intergroup comparison of heat tolerance [n(%)]

Variable	Low heat tolerance(n=1 726)	Moderate heat tolerance(n=546)	Strong heat tolerance(n=324)	χ^2	P
I get sick more easily than others				440.973	<0.001
Frequently	459(90.2)	42(8.3)	8(1.6)		
Unsure	836(71.2)	249(21.2)	89(7.6)		
Mostly incorrect	355(53.5)	187(28.2)	121(18.3)		
Absolutely incorrect	76(30.4)	68(27.2)	106(42.4)		
I am as healthy as others				210.775	<0.001
Rarely	123(85.4)	11(7.6)	10(6.9)		
Unsure	624(78.0)	134(16.8)	42(5.3)		
Mostly correct	781(63.5)	300(24.4)	148(12.0)		
Absolutely correct	198(46.8)	101(23.9)	124(29.3)		
I feel my health is deteriorating				376.434	<0.001
Frequently	503(88.2)	53(9.3)	14(2.5)		
Unsure	720(72.8)	191(19.3)	78(7.9)		
Mostly incorrect	363(52.9)	210(30.6)	113(16.5)		
Absolutely incorrect	140(39.9)	92(26.2)	119(33.9)		
My health is in excellent condition				359.910	<0.001
Rarely	184(93.4)	11(5.6)	2(1.0)		
Unsure	723(80.2)	132(14.6)	47(5.2)		
Mostly correct	695(59.0)	322(27.4)	160(13.6)		
Absolutely correct	124(38.8)	81(25.3)	115(35.9)		
Appetite				262.754	<0.001
Very poor	44(88.0)	3(6.0)	3(6.0)		
Relatively poor	254(89.4)	29(10.2)	1(0.4)		
Average	818(73.2)	229(20.5)	71(6.4)		
Relatively good	504(55.8)	224(24.8)	176(19.5)		
Very good	106(44.2)	61(25.4)	73(30.4)		
Sleep quality				262.754	<0.001
Very poor	79(86.8)	11(12.1)	1(1.1)		
Relatively poor	356(83.6)	63(14.8)	7(1.6)		
Average	681(69.9)	210(21.6)	83(8.5)		
Relatively good	515(58.1)	218(24.6)	154(17.4)		
Very good	95(43.6)	44(20.2)	79(36.2)		
Underlying diseases				116.056	<0.001
Yes	696(79.7)	135(15.5)	42(4.8)		
No	1 030(59.8)	411(23.9)	282(16.4)		
Fatigue or drowsiness at rest				558.647	<0.001
Frequently	185(88.5)	20(9.6)	4(1.9)		
Often	342(84.0)	55(13.5)	10(2.5)		
Occasionally	790(72.0)	246(22.4)	61(5.6)		
Rarely	324(54.7)	160(27.0)	108(18.2)		
Hardly	85(29.2)	65(22.3)	141(48.5)		

表3 行为特征及与热耐力的组间比较[例(%)]

Table 3 Behavioral characteristics and intergroup comparison of heat tolerance [n(%)]

Variable	Low heat tolerance (n=1 726)	Moderate heat tolerance (n=546)	Strong heat tolerance (n=324)	χ^2	P
Daily smoking				12.168	0.002
Yes	85(54.8)	39(25.2)	31(20.0)		
No	1 641(67.2)	507(20.8)	293(12.0)		
Daily water intake/L				51.410	<0.001
<1	486(73.3)	129(19.5)	48(7.2)		
1 to 2	1 005(66.6)	316(20.9)	189(12.5)		
>2	235(55.6)	101(23.9)	87(20.6)		
Daily sleep duration/h				55.747	<0.001
<6	292(74.3)	83(21.1)	18(4.6)		
6 to <7	825(68.9)	244(20.4)	128(10.7)		
7 to <8	85(63.4)	27(20.1)	22(16.4)		
≥8	524(60.1)	192(22.0)	156(17.9)		
Monthly frequency of staying up late				35.839	<0.001
≥9 times	831(71.0)	225(19.2)	114(9.7)		
5 to 8 times	291(66.4)	97(22.1)	50(11.4)		
1 to 4 times	428(62.0)	162(23.5)	100(14.5)		
Very rarely or none	176(59.1)	62(20.8)	60(20.1)		
Weekly exercise frequency/times				105.680	<0.001
1	906(73.4)	240(19.4)	89(7.2)		
2 to 3	587(63.5)	195(21.1)	142(15.4)		
4 to 5	140(59.1)	61(25.7)	36(15.2)		
>5	93(46.5)	50(25.0)	57(28.5)		
Duration of each exercise session/min				73.148	<0.001
<40	1 195(71.6)	314(18.8)	159(9.5)		
40 to 50	256(61.7)	101(24.3)	58(14.0)		
50 to 60	87(53.0)	43(26.2)	34(20.7)		
>60	188(53.9)	88(25.2)	73(20.9)		
Exercise categories				45.481	<0.001
None	176(73.9)	46(19.3)	16(6.7)		
1 type	1 118(69.4)	309(19.2)	184(11.4)		
2 types	342(59.4)	137(23.8)	97(16.8)		
≥3 types	90(52.6)	54(31.6)	27(15.8)		

果显示:VIF最大值为2.158,远低于10的临界值;容忍度最小值为0.463,高于0.1的标准。自变量间共线性程度较低,符合回归分析要求。

2.3.2 多项Logistic回归分析 因为平行线检验拒绝比例优势假设(P<0.001),本研究采用多项Logistic回归。以"低热耐力"为参照组,将χ^2检验筛选出的22项显著因素作为初始变量,经向后步进法逐步剔除,最终保留13个变量。模型整体显著(χ^2=1 044.602,df=72,P<0.001),解释方差为40.4%(R^2=0.404),拟合效果良好。

多项Logistic回归分析结果显示,女性达到中等、强热耐力的可能性较男性降低50.4%[OR=0.496(95%CI:0.390~0.631),P<0.001]和75.0%[OR=0.250(95%CI:0.178~0.349),P<0.001];16~18岁群体达到中等、强热耐力的可能性是≥26岁群体的2.091倍(95%CI:1.330~3.288,P=0.001)和3.778倍

表4 环境适应行为与热耐力的组间比较[例(%)]

Table 4 Environmental adaptation behaviors and intergroup comparison of heat tolerance [n(%)]

Variable	Low heat tolerance (n=1 726)	Moderate heat tolerance (n=546)	Strong heat tolerance (n=324)	χ^2	P
Increase shower frequency in high temperatures				30.288	<0.001
Never	81(56.6)	36(25.2)	26(18.2)		
Occasionally	245(63.3)	83(21.4)	59(15.2)		
Sometimes	395(61.2)	156(24.2)	94(14.6)		
Frequently	1 005(70.7)	271(19.1)	145(10.2)		
Wear a hat when going out in high temperatures				39.706	<0.001
Never	515(60.0)	208(24.2)	136(15.8)		
Occasionally	416(65.3)	138(21.7)	83(13.0)		
Sometimes	334(69.0)	95(19.6)	55(11.4)		
Frequently	461(74.8)	105(17.0)	50(8.1)		

表5 人际网络与热耐力的组间比较[例(%)]

Table 5 Interpersonal network and intergroup comparison of heat tolerance [n(%)]

Variable	Low heat tolerance (n=1 726)	Moderate heat tolerance (n=546)	Strong heat tolerance (n=324)	χ^2	P
Pay attention to weather forecasts				26.707	<0.001
Never	53(56.4)	21(22.3)	20(21.3)		
Occasionally	302(60.6)	116(23.3)	80(16.1)		
Sometimes	489(65.4)	160(21.4)	99(13.2)		
Frequently	882(70.2)	249(19.8)	125(10.0)		
Seek medical attention or help promptly in case of heatstroke				24.192	<0.001
Never	60(60.6)	22(22.2)	17(17.2)		
Occasionally	234(71.1)	72(21.9)	23(7.0)		
Sometimes	512(68.3)	165(22.0)	73(9.7)		
Frequently	920(64.9)	287(20.2)	211(14.9)		

(95%*CI*:2.028~7.039,*P*<0.001);未经历过热浪者达到中等、强热耐力显著降低42.1%[*OR*=0.579(95%*CI*:0.371~0.903),*P*=0.016]和52.5%[*OR*=0.475(95%*CI*:0.257~0.878),*P*=0.017]。详见表6。

2.4 健康生态学各维度对热耐力的路径分析

本研究以健康生态学模型为框架,基于多项Logistic回归中的显著变量以及因子分析验证的维度,构建结构方程模型。模型包含个人特质、行为特征及环境适应行为3个潜变量,人际网络维度因信效度不足予以删除,符合多项Logistic回归中该维度相关变量不显著的结果,采用加权最小二乘法作为估计方法。模型拟合良好(χ^2/df=2.957,GFI=0.996,CFI=0.992,TLI=0.990,RMSEA=0.030,SRMR=0.042)。结果显示,个人特质(β=0.696,*P*<0.001)与环境适应行为(β=−0.143,*P*<0.001)对热耐力有显著影响,而行为特征的直接影响不显著(*P*=0.871)。模型路径及参数估计详见图1和表7。

2.5 社会人口学特征对热耐力的路径分析

性别对热耐力具有显著的正向直接影响(图2A),直接效应值为0.261(95%*CI*:0.206~0.316)。个人特质在性别与热耐力之间起到显著的中介作用,效应值为0.185(95%*CI*:0.156~0.216),效应量远大于其他间接路径,接近直接效应的70%。环境适应行为在性别与热耐力之间起到较小但显著的中介作用,效应值为0.008(95%*CI*:0.002~0.015)。行为特征在性别与热耐力之间的中介效应未达统计学显著性,置信区间−0.029~0.016中包括0。

年龄对热耐力具有显著负向直接影响(图2B),直接效应值为−0.067(95%*CI*:−0.094~−0.039)。个人特质在年龄与热耐力之间起到显著的正向中介作用,

表6 热耐力影响因素的多项Logistic回归分析

Table 6 Multinomial logistic regression analysis of factors influencing heat tolerance

Predictor variable (reference group)	Moderate heat tolerance			Strong heat tolerance		
	B(*SE*)	*Sig.*	*OR*(95%*CI*)	*B*(*SE*)	*Sig.*	*OR*(95%*CI*)
Intercept	0.858(0.448)	0.056	-	1.972(0.547)	<0.001	-
Gender(Male)						
Female	−0.702(0.123)	<0.001	0.496(0.390—0.631)	−1.388(0.171)	<0.001	0.250(0.178—0.349)
Age(≥26 years old)/years						
16 to 18	0.738(0.231)	0.001	2.091(1.330—3.288)	1.329(0.317)	<0.001	3.778(2.028—7.039)
19 to 21	0.415(0.229)	0.070	1.514(0.966—2.373)	0.649(0.321)	0.043	1.913(1.021—3.586)
22 to 25	0.181(0.286)	0.526	1.199(0.685—2.098)	0.717(0.377)	0.057	2.049(0.979—4.288)
I get sick more easily than others(Absolutely incorrect)						
Frequently	−1.435(0.272)	<0.001	0.238(0.140—0.406)	−2.506(0.450)	<0.001	0.082(0.034—0.197)
Unsure	−0.638(0.220)	0.004	0.528(0.343—0.813)	−1.301(0.260)	<0.001	0.272(0.164—0.453)
Mostly incorrect	−0.326(0.219)	0.137	0.722(0.470—1.109)	−0.726(0.247)	0.003	0.484(0.298—0.785)
I feel my health is deteriorating(Absolutely incorrect)						
Frequently	−0.615(0.252)	0.014	0.540(0.330—0.885)	−0.726(0.387)	0.061	0.484(0.226—1.034)
Unsure	−0.176(0.210)	0.404	0.839(0.556—1.267)	−0.111(0.273)	0.686	0.895(0.524—1.530)
Mostly incorrect	0.303(0.202)	0.133	1.353(0.912—2.009)	0.262(0.249)	0.292	1.300(0.798—2.116)
My health is in excellent condition(Absolutely correct)						
Rarely	−0.975(0.390)	0.012	0.377(0.176—0.810)	−1.850(0.898)	0.039	0.157(0.027—0.914)
Unsure	−0.277(0.233)	0.234	0.758(0.480—1.197)	−0.141(0.313)	0.652	0.868(0.470—1.604)
Mostly correct	0.024(0.202)	0.907	1.024(0.689—1.521)	−0.226(0.242)	0.349	0.797(0.496—1.281)
Appetite(Very good)						
Very poor	−0.480(0.681)	0.481	0.619(0.163—2.349)	1.039(0.993)	0.295	2.827(0.404—19.779)
Relatively poor	−0.609(0.292)	0.037	0.544(0.307—0.965)	−2.748(1.058)	0.009	0.064(0.008—0.510)
Average	−0.210(0.215)	0.330	0.811(0.532—1.237)	−0.385(0.280)	0.168	0.680(0.393—1.177)
Relatively good	−0.069(0.206)	0.738	0.933(0.623—1.399)	0.303(0.249)	0.223	1.354(0.831—2.205)
Sleep quality(Very good)						
Very poor	0.226(0.434)	0.603	1.253(0.535—2.936)	−2.227(1.132)	0.049	0.108(0.012—0.992)
Relatively poor	−0.029(0.265)	0.912	0.971(0.577—1.633)	−1.762(0.472)	<0.001	0.172(0.068—0.433)
Average	0.088(0.231)	0.704	1.092(0.694—1.718)	−0.767(0.269)	0.004	0.464(0.274—0.787)
Relatively good	0.065(0.224)	0.773	1.067(0.688—1.654)	−0.602(0.246)	0.014	0.547(0.338—0.887)
Underlying diseases(No)						
Yes	−0.312(0.121)	0.010	0.732(0.577—0.929)	−0.874(0.205)	<0.001	0.417(0.279—0.624)
Experienced Heatwave Events(Yes)						
No	−0.547(0.227)	0.016	0.579(0.371—0.903)	−0.744(0.313)	0.017	0.475(0.257—0.878)
Fatigue or drowsiness at rest(Hardly)						
Frequently	−0.698(0.319)	0.029	0.497(0.266—0.93)	−2.075(0.577)	<0.001	0.126(0.040—0.389)
Often	−0.577(0.248)	0.020	0.562(0.345—0.914)	−2.227(0.391)	<0.001	0.108(0.050—0.232)
Occasionally	−0.317(0.203)	0.119	0.728(0.489—1.084)	−1.981(0.234)	<0.001	0.138(0.087—0.218)
Rarely	−0.274(0.208)	0.187	0.760(0.506—1.142)	−1.118(0.215)	<0.001	0.327(0.215—0.498)
Weekly exercise frequency(>5 times)/times						
1	0.077(0.226)	0.732	1.080(0.693—1.683)	−0.438(0.282)	0.121	0.646(0.371—1.123)
2 to 3	−0.046(0.222)	0.838	0.955(0.618—1.478)	−0.215(0.266)	0.421	0.807(0.479—1.360)
4 to 5	−0.200(0.257)	0.437	0.819(0.494—1.355)	−0.926(0.327)	0.005	0.396(0.209—0.751)
Exercise Categories(≥3 types)						
None	−0.296(0.280)	0.292	0.744(0.429—1.289)	0.395(0.446)	0.376	1.484(0.619—3.556)
1 type	−0.295(0.220)	0.179	0.744(0.484—1.145)	0.746(0.317)	0.018	2.109(1.134—3.924)
2 types	−0.281(0.226)	0.213	0.755(0.485—1.175)	0.533(0.321)	0.097	1.704(0.909—3.196)
Increase shower frequency in high temperatures(Frequently)						
Never	0.730(0.238)	0.002	2.075(1.303—3.306)	0.999(0.326)	0.002	2.716(1.435—5.141)
Occasionally	0.201(0.156)	0.198	1.222(0.900—1.659)	0.652(0.215)	0.002	1.920(1.260—2.926)
Sometimes	0.300(0.127)	0.018	1.350(1.052—1.732)	0.452(0.185)	0.014	1.572(1.095—2.257)

表7 健康生态学模型结构方程路径系数

Table 7 Path coefficients of the health ecological model by structural equation modeling

Path	Unstandardized path coefficient	*SE*	*Z*	*P*	Standardized path coefficient
Personal traits—Heat tolerance	0.968	0.035	27.948	<0.001	0.696
Behavioral characteristics—Heat tolerance	0.006	0.038	0.162	0.871	0.005
Environmental adaptation behaviors—Heat tolerance	−0.242	0.050	−4.798	<0.001	−0.143
Behavioral characteristics—Personal traits	0.401	0.026	15.311	<0.001	0.437

效应值为0.038(95%*CI*:0.022~0.055),是中介效应的主要贡献路径。个人特质和行为特征构成的链式中介路径虽然达到统计学显著,但是效应较小,效应值为0.001(95%*CI*:0.001~0.003)。其他中介路径均未达到统计学显著性。

经历热浪事件对热耐力具有显著正向直接影响(图2C),直接效应值为0.106(95%*CI*:0.002~0.209)。环境适应行为在经历热浪事件与热耐力之间起到显著的正向中介作用,效应值为0.018(95%*CI*:0.027~0.037),是唯一显著的中介路径。

3 讨论

3.1 男性热耐力高于女性

性别对热耐力具有显著正向影响,总效应值为0.443。男性的优势既体现在生理上的直接效应(标准化路径系数为0.261),也体现在通过个人特质产生的间接效应(标准化路径系数为0.185),后者贡献了总效应的41.70%,表明个人特质是性别影响热耐力的关键中介路径。具体而言,男性在强、中、低热耐力中分布相对均衡(24.2%、27.0%、48.8%),而女性高度集中于低热耐力(75.5%),仅6.5%达到强耐力水

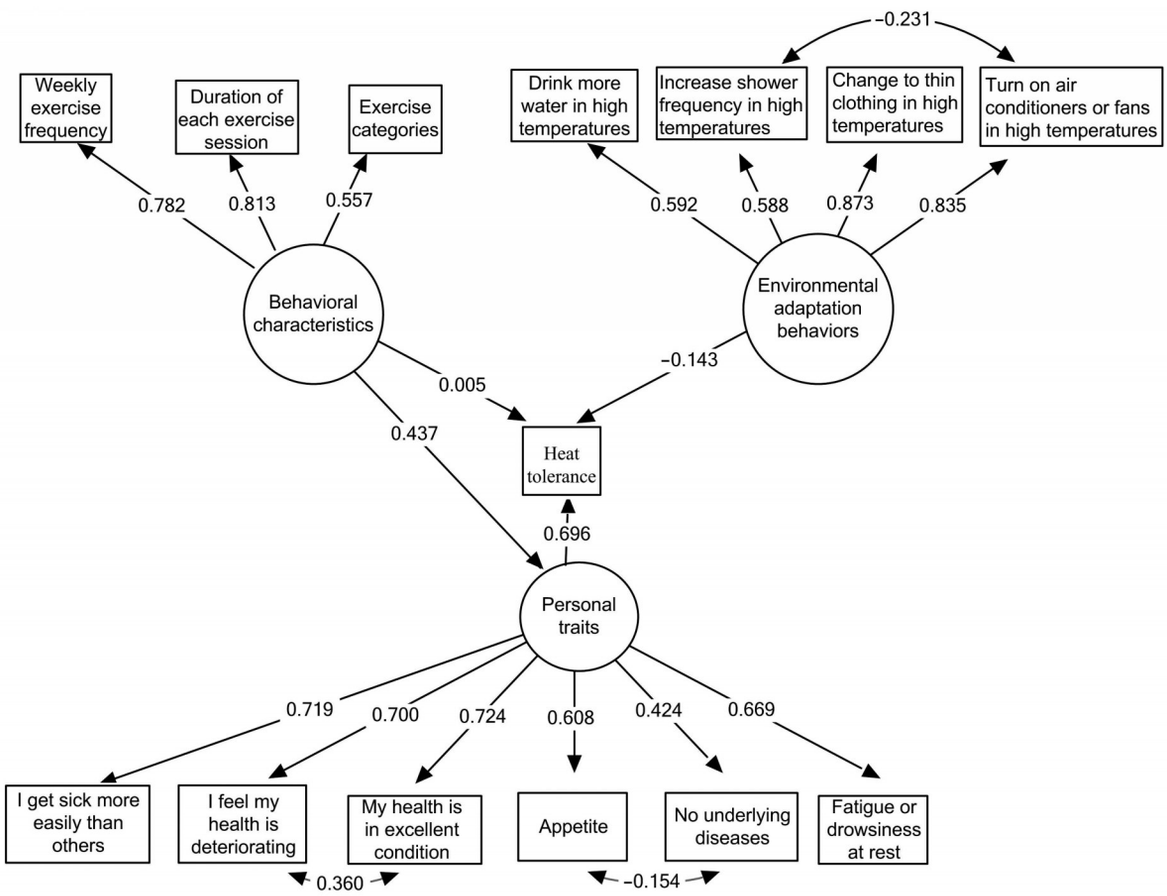
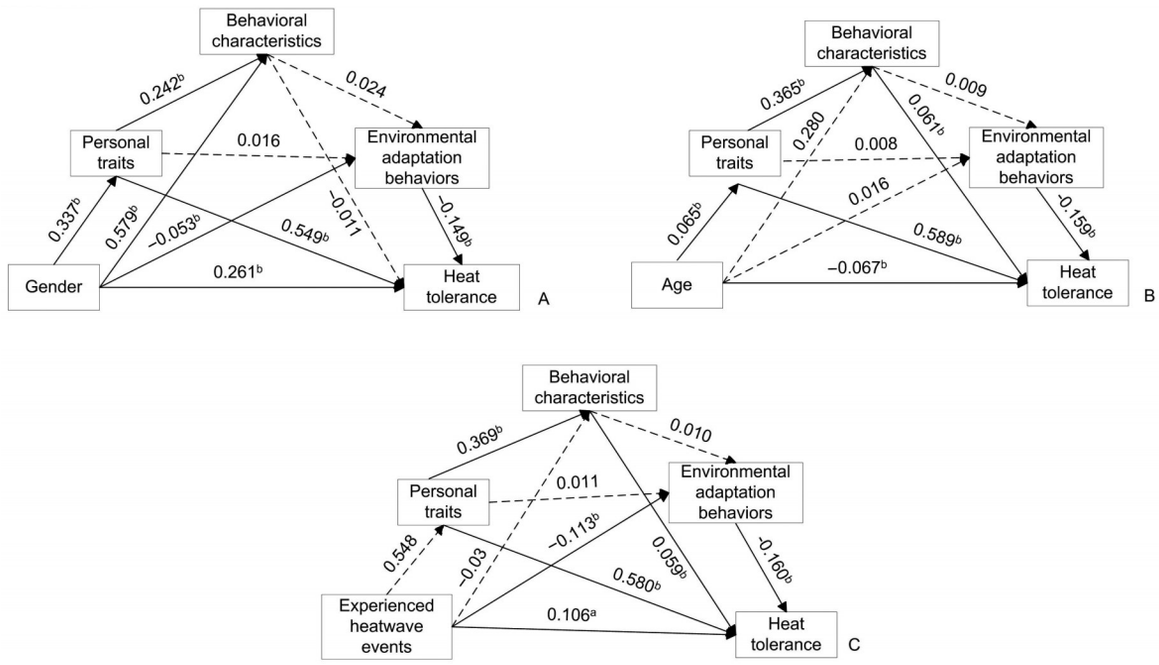


图1 健康生态学模型结构方程路径图

Figure 1 Structural equation path diagram of the health ecological model



A: Pathway analysis of gender and heat tolerance; B: Pathway analysis of age and heat tolerance; C: Pathway analysis of experienced heatwave events and heat tolerance. a: $P<0.05$, b: $P<0.01$

图2 社会人口学特征与热耐力的路径分析

Figure 2 Pathway analysis of sociodemographic characteristics and heat tolerance

平。多项Logistic回归进一步证实,女性达到中等[*OR*=0.496(95%*CI*:0.390~0.631)]和强热耐力[*OR*=0.250(95%*CI*:0.178~0.349)]的概率仅分别为男性的0.496倍和0.250倍。该结果与现有文献一致,WOLF等[12]研究证实,在未热习服人群中,绝对代谢率校正后,女性的临界热耐力极限显著低于男性,且性别是热耐力的独立预测因素。WICKHAM等[13]发现女性需要更长的热习服时间才能达到与男性相当的生理适应水平。ALELE等[14]的系统综述也表明女性发生劳力性热相关疾病的风险更高。

3.2 年龄对热耐力存在"直接负向、间接正向"的双向路径

年龄是影响热耐力的显著因素。与≥26岁的参与者相比,16~18岁[*OR*=3.778(95%*CI*:2.028~7.039)]和19~21岁[*OR*=1.913(95%*CI*:1.021~3.586)]的参与者表现出更高概率的强热耐力。尽管年龄增长直接削弱热耐力(标准化路径系数为-0.067),但可通过提升个人特质间接发挥积极作用(标准化路径系数为0.038)。综上,强化个人特质可抵消高达56.7%的年龄对热耐力的直接负面影响,从而有效缓解年龄增长带来的负面效应。

3.3 个人特质是影响热耐力的核心因素

个人特质是热耐力最关键的决定因素(标准化路径系数为0.696),其解释力远超行为特征与环境适应行为,同时也是性别、年龄和行为特征等因素影响热耐力的重要中介。个人特质由6个观测变量构成,其中积极的健康感知贡献最大,"健康状况好"(因子载荷0.724)、"不认为容易生病"(因子载荷0.719)和"不认为健康变坏"(因子载荷0.700)是核心成分。其次是生理状态,"静息时乏力困倦"(因子载荷0.669)和"食欲"(因子载荷0.608)也具有较强关联,而"无基础疾病"(因子载荷0.424)贡献相对较小。回归分析进一步证实:消极的健康感知是热耐力最强的负面预测因子。具体而言,认为自己比别人容易生病者达到中等和强热耐力的可能性分别降至23.8%和8.2%,认为健康状况在变坏者达到中等和强热耐力的可能性分别降至54.0%和48.4%,不认为健康状况良好者达到中等和强热耐力的可能性分别降至37.7%和15.7%,有基础疾病者达到中等、强热耐力的可能性分别降至73.2%和41.7%,静息乏力和困倦者达到中等和强热耐力的可能性分别降至49.7%和12.6%。结果表明,负面健康感知、生理状态欠佳和基础疾病对热耐力的负面影响具有统计学意义,尤其对强热耐力的削弱效应最为强烈。

3.4 行为特征通过提升个人特质增强热耐力

行为特征虽对热耐力无显著的直接效应,但可通

过提升个人特质间接增强热耐力[15-16](标准化路径系数为0.304)。然而,该间接效应的发挥受健身方式的影响:专注单一项目可显著提升强热耐力[*OR*=2.109(95%*CI*:1.134~3.924)],而每周健身4~5次的过度训练则构成风险因素,使强热耐力显著降低[*OR*=0.396(95%*CI*:0.209~0.751)],其余锻炼类型或频率对风险的影响未达统计学显著。综上,适度且专注是行为特征促进热耐力的关键前提。

3.5 环境适应行为对热耐力具有抑制作用

环境适应行为对热耐力存在显著的负向预测作用(标准化路径系数为-0.143),表明过度依赖空调、主动躲避炎热等行为,可能因热刺激不足而导致生理热适应能力退化[17-18]。相比之下,经历热浪事件不仅对热耐力具有微弱的直接促进作用(标准化路径系数为0.106),还通过减少对环境适应行为的依赖,间接地维持或提升个体的热耐力(标准化路径系数为0.018)。

本次调查存在3个方面的局限:①变量测量以主观指标为主,缺乏客观生理指标。尽管采用严格的量表信效度检验保障了主观测量的可靠性,且大样本量提升了结果的统计稳定性,但主观指标易受认知、情绪与报告偏倚影响[19],且未纳入核心体温、出汗率、心率变异性、有氧耐力等客观指标及环境变量[20-21],限制热耐力及影响因素的因果解析,降低生理层面的解释力。②方便抽样导致研究人群的代表性不足。虽然调查最终获得2 596份有效样本,且研究对象年龄、学历等特征在高校师生群体中具有一定的代表性,但研究对象以中青年、高学历群体为主,且均为日常以脑力活动为主的低热暴露、低体力负荷人群,缺乏对高龄低学历人群、户外体力劳动者、高温作业从业者等热耐力高风险人群的覆盖。③健康生态学模型维度覆盖不足。本研究基于健康生态学框架,整合个人特质、行为特征与环境适应等维度,初步揭示热耐力的多层影响并获得理论验证,但因信效度问题未分析人际网络,未涵盖社会经济、政策、设施等宏观因素,限制了对热耐力综合作用机制的全面解析。未来研究优化方向:①优化测量工具与指标体系,结合主观问卷与客观检测;②采用纵向研究设计,明确各因素与热耐力之间的因果关系及动态作用路径;③扩大研究人群范围,优化抽样方法,提升研究结论的外推性与普适性;④完善健康生态学研究框架。

本研究从健康生态学模型的4个层面分析热耐力的影响因素,发现个人特质是影响热耐力的关键因素,行为特征本身并不直接影响热耐力,而是先改善个人特质再间接起效,环境适应行为对热耐力存在显著的负向效应,但人际网络的影响不显著。本研究结论基于重庆市低热暴露-低体力负荷的高校师生群体得出,外推至其他人群时需结合人群特征综合考量。

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参考文献:

[1] 宋景春, 宋青, 宁波, 等. 劳力性中暑官兵热耐力重建技术方案(第1版)[J]. 解放军医学杂志, 2024, 49(4): 367-370. DOI:10.11855/j.issn.0577-7402.1643.2024.0122.
SONG J C, SONG Q, NING B, *et al*. Reconstructing technology program for heat endurance of soldiers with exertional heat illness (first edition)[J]. Med J Chin PLA, 2024, 49(4): 367-370. DOI: 10.11855/j. issn. 0577-7402.1643.2024.0122.

[2] 刘磊, 谷利群, 韩玉明, 等. 部队官兵热耐力状况评价方法的探讨[J]. 空军航空医学, 2024, 41(6): 536-539. DOI: 10.3969/j.issn.2097-1753.2024.06.012.
LIU L, GU L Q, HAN Y M, *et al*. Evaluation methods for thermal endurance status of troops[J]. Aviat Med Air Force, 2024, 41(6): 536-539. DOI: 10.3969/j. issn. 2097-1753.2024.06.012.

[3] 马骏, 李磊, 宋青. 热耐力测试在热射病防治中的应用[J]. 武警医学, 2024, 35(11): 1008-1012. DOI:10.3969/j.issn.1004-3594.2024.11.023.
MA J, LI L, SONG Q. Application of thermal endurance test in the prevention and treatment of thermal radiation disease[J]. Med J Chin People's Armed Police Forces, 2024, 35(11): 1008-1012. DOI: 10.3969/j. issn. 1004-3594.2024.11.023.

[4] 王岩岩, 王芹, 徐伟, 等. 164例中暑患者的特征及进展为热射病的相关因素分析[J]. 陆军军医大学学报, 2025, 47(10): 1043-1048. DOI:10.16016/j.2097-0927.202502020.
WANG Y Y, WANG Q, XU W, *et al*. Clinical features of heat illness and related factors for progression to heatstroke: an analysis of 164 cases[J]. J Army Med Univ, 2025, 47(10): 1043-1048. DOI:10.16016/j.2097-0927.202502020.

[5] PÉRIARD J D, TRAVERS G J S, RACINAIS S, *et al*. Cardiovascular adaptations supporting human exercise-heat acclimation[J]. Auton Neurosci, 2016, 196: 52-62. DOI: 10.1016/j.autneu.2016.02.002.

[6] ALELE F O, MALAU-ADULI B S, MALAU-ADULI A E O, *et al*. Individual anthropometric, aerobic capacity and demographic characteristics as predictors of heat intolerance in military populations[J]. Medicina, 2021, 57(2): 173. DOI:10.3390/medicina57020173.

[7] MCLEROY K R, BIBEAU D, STECKLER A, *et al*. An ecological perspective on health promotion programs[J].

Health Educ Q, 1988, 15(4): 351-377. DOI: 10.1177/109019818801500401.

[8] 高永祥, 张晋昕. Logistic回归分析的样本量确定[J]. 循证医学, 2018, 18(2): 122-124. DOI: 10.12019/j.issn.1671-5144.2018.02.015.
GAO Y X, ZHANG J X. Determination of sample size in logistic regression analysis[J]. J Evid Based Med, 2018, 18(2): 122-124. DOI: 10.12019/j.issn.1671-5144.2018.02.015.

[9] MACCALLUM R C, BROWNE M W, SUGAWARA H M. Power analysis and determination of sample size for covariance structure modeling[J]. Psychol Meth, 1996, 1(2): 130-149. DOI: 10.1037/1082-989x.1.2.130.

[10] 中国公民健康素养: 基本知识与技能(2015年版)[J]. 中国健康教育, 2016, 32(1): 94-95.
China citizens' health literacy-basic knowledge and skills (2015 edition)[J]. Chin J Health Educ, 2016, 32(1): 94-95.

[11] 陈家俊, 王静. 热习服训练方案及评价指标的研究进展[J]. 军事医学, 2020, 44(6): 465-469, 480.
CHEN J J, WANG J. Research progress in heat acclimatization training protocol and evaluation index[J]. Mil Med Sci, 2020, 44(6): 465-469, 480.

[12] WOLF S T, BERNARD T E, KENNEY W L. Heat exposure limits for young unacclimatized males and females at low and high humidity[J]. J Occup Environ Hyg, 2022, 19(7): 415-424. DOI: 10.1080/15459624.2022.2076859.

[13] WICKHAM K A, WALLACE P J, CHEUNG S S. Sex differences in the physiological adaptations to heat acclimation: a state-of-the-art review[J]. Eur J Appl Physiol, 2021, 121(2): 353-367. DOI: 10.1007/s00421-020-04550-y.

[14] ALELE F, MALAU-ADULI B, MALAU-ADULI A, *et al*. Systematic review of gender differences in the epidemiology and risk factors of exertional heat illness and heat tolerance in the armed forces[J]. BMJ Open, 2020, 10(4): e031825. DOI: 10.1136/bmjopen-2019-031825.

[15] LISMAN P, KAZMAN J B, O'CONNOR F G, *et al*. Heat tolerance testing: association between heat intolerance and anthropometric and fitness measurements[J]. Mil Med, 2014, 179(11): 1339-1346. DOI: 10.7205/MILMED-D-14-00169.

[16] 宋用为, 王玲, 陈文婷, 等. 罗沙司他通过上调HIF-1α减轻热打击诱导的肾小管上皮细胞凋亡与衰老[J]. 陆军军医大学学报, 2024, 46(10): 1092-1099. DOI: 10.16016/j.2097-0927.202312123.
SONG Y W, WANG L, CHEN W T, *et al*. Roxadustat attenuates heat stress-induced apoptosis and senescence in renal tubular epithelial cells by upregulating HIF-1α[J]. J Army Med Univ, 2024, 46(10): 1092-1099. DOI: 10.16016/j.2097-0927.202312123.

[17] 李代波, 曾岚, 银涛, 等. 热区某特种部队中暑现状及个体易感因素调查研究[J]. 第三军医大学学报, 2017, 39(4): 337-341. DOI: 10.16016/j.1000-5404.201606171.
LI D B, ZENG L, YIN T, *et al*. Survey on status and individual susceptible factors of heat stroke in a troop of special forces stationed in thermal region[J]. J Third Mil Med Univ, 2017, 39(4): 337-341. DOI: 10.16016/j.1000-5404.201606171.

[18] 李海波, 陈佩延, 陈高飞, 等. 适宜现场应用的热习服评价敏感指标识别分析[J]. 军事医学, 2023, 47(6): 401-406.
LI H B, CHEN P Y, CHEN G F, *et al*. Sensitive indexes for on-the-scene heat acclimatization evaluation[J]. Mil Med Sci, 2023, 47(6): 401-406.

[19] MOORE A C, STACEY M J, BAILEY K G H, *et al*. Risk factors for heat illness among British soldiers in the hot Collective Training Environment[J]. J R Army Med Corps, 2016, 162(6): 434-439. DOI: 10.1136/jramc-2015-000427.

[20] SCHERMANN H, CRAIG E, YANOVICH E, *et al*. Probability of heat intolerance: standardized interpretation of heat-tolerance testing results versus specialist judgment[J]. J Athl Train, 2018, 53(4): 423-430. DOI: 10.4085/1062-6050-519-16.

[21] KENNY G P, GROELLER H, MCGINN R, *et al*. Age, human performance, and physical employment standards[J]. Appl Physiol Nutr Metab, 2016, 41(6 (Suppl. 2)): S92-S107. DOI: 10.1139/apnm-2015-0483.

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