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Aims and Scope

The *Korean Journal of Health Promotion (KJHP)* is an open access, multidisciplinary journal dedicated to publishing high-quality research in various areas of the medical, nursing, nutritional, physical educational, epidemiological, and public health sciences associated with health promotion and disease prevention. *KJHP*, which has been published continuously since 2001, is an official journal of the Korean Society for Health Promotion and Disease Prevention.

The aim of the *KJHP* is to advance and disseminate new knowledge and scientific information in all the areas associated with health promotion and disease prevention. KJHP publishes original articles, narrative reviews, systematic reviews and meta-analyses, letters to the editor, and perspectives in English.

Abbreviation
The correct abbreviation for abstracting and indexing purposes is *Korean J Health Promot*.

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Can AI Health Conversations Serve as a New Mediator of Health Behavior Change?

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ABSTRACT

Health conversations with artificial intelligence (AI) chatbots are rapidly increasing; 17% of US adults consult AI chatbots about health monthly, and the figure reaches 25% among those under 30. In Korea, generative AI use reached 33.3% in 2024, nearly doubling from the previous year. Yet academic discourse has largely focused on information accuracy and patient safety. I propose reframing AI health conversations as a potential mediator of health behavior change. Drawing on systematic reviews showing that AI chatbots can support physical activity and smoking cessation, I connect these findings to the transtheoretical model processes of change and the health belief model construct of self-efficacy. I describe the "information-to-action question shift" as a mechanism that may drive the transition from contemplation to action, and discuss intersections with Korea's Fifth National Health Plan (HP2030) health literacy goals.

Keywords: Artificial intelligence, Health promotion, Health behavior, Self efficacy, Health literacy

INTRODUCTION

In June 2024, a Kaiser Family Foundation survey of 2,428 US adults found that 17% had consulted artificial intelligence (AI) chatbots about health-related matters at least once a month, with this proportion reaching 25% among those under 30 [1]. Korea is no exception. The Ministry of Science and ICT's 2024 internet usage survey reported that AI service use in Korea reached 60.3%, and generative AI use was 33.3%—nearly double the 17.6% of the previous year—with over 80% of adults in their 20s and 30s having tried such services [2]. The Korea Information Society Development Institute reported AI chatbot use at 13.4% in its 2023 Korean media panel survey, mostly for information searching [3]. The pattern is clear: AI health conversations are no longer confined to a small group of technology adopters. They are becoming mainstream.

Yet academic discourse on this phenomenon has remained within two frames: the accuracy of health information that AI provides and its impact on the physician–patient relationship. A different question deserves attention—one that the health promotion field has largely overlooked. Can AI health conversations serve as a mediator that moves consumers toward health behavior change? We explore this question through the lens of health promotion theory.

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MAIN BODY

AI chatbots and health behavior change: existing evidence

Evidence on the behavior change effects of AI chatbot interventions is accumulating. Aggarwal et al. [4], in a systematic review of 15 studies published in Journal of Medical Internet Research, found that AI chatbots were effective in promoting healthy lifestyles (40%), smoking cessation (27%), and treatment adherence (20%). Singh et al. [5] extended this work with a meta-analysis of 19 studies in NPJ Digital Medicine, showing that chatbot interventions significantly increased total physical activity (standardized mean difference [SMD]=0.28; 95% confidence interval [CI], 0.16–0.40), moderate-to-vigorous physical activity (SMD=0.53; 95% CI, 0.24–0.83), and fruit and vegetable intake (SMD=0.59; 95% CI, 0.25–0.93). A more recent systematic review of natural language processing-based chatbot interventions confirmed consistent effects on smoking cessation, with users rating chatbots as useful and trustworthy.

An important caveat applies: these studies examined pre-designed, rule-based, or task-specific chatbots—not the general-purpose large language model (LLM)-based conversations that consumers now use freely. Direct comparison is difficult. Still, general-purpose LLMs may offer greater natural language flexibility, context maintenance, and personalization than earlier rule-based chatbots, so the behavior change effects identified in existing research may well be maintained or even amplified. At minimum, the available evidence suggests that conversational interaction with AI can function as a mediator of health behavior change.

Theoretical mechanisms: how AI conversations drive behavior change

Can the behavior change effects of AI chatbots be explained by health promotion theory? We attempt to connect them with two established models.

Transtheoretical model and the processes of change

The transtheoretical model (TTM) of Prochaska and DiClemente [6] explains behavior change through five stages—precontemplation, contemplation, preparation, action, and maintenance—and proposes 10 processes of change that enable transitions between stages.

AI health conversations connect with at least three of these processes. Consider "consciousness raising." When a user tells an AI chatbot, "I've been feeling tired lately," the chatbot responds with follow-up questions about sleep duration, dietary habits, and stress levels, thereby sharpening awareness of one's own condition. Repeated conversations may then trigger "self-reevaluation"—a cognitive shift such as "I thought I was fairly healthy, but I actually have multiple risk factors." And when an AI chatbot presents specific, achievable behavioral options—"the smallest action you can take within 10 minutes after leaving work"—it may strengthen behavioral commitment, a process that aligns with "self-liberation."

A noteworthy phenomenon is the "information-to-action question shift" I observed in AI health conversations. In one case involving a worker in their 40s (pseudonym), approximately 200 health questions were posed over three months ("What foods are good for fatty liver?" "What medication should I take for high triglycerides?"), with no change in weight. But when the questions shifted toward action—"Could I take a 10-minute walk on the way to the convenience store after work?"—walking behavior was initiated (author's observation, unpublished). In TTM terms, this corresponds to a transition from the contemplation stage (information gathering) to the preparation-action stage (execution planning). The shift bears conceptual similarity to the process in motivational interviewing where change talk develops into commitment language, although it has not been systematically verified in the AI conversation context. Because this is a single observational case, caution is warranted in generalizing; large-scale empirical verification is needed.

Health belief model and self-efficacy

The health belief model (HBM) explains health behavior through six constructs: perceived susceptibility, perceived severity, perceived benefits, perceived barriers, cues to action, and self-efficacy [7]. AI health conversations are likely to operate most strongly on two of these: self-efficacy and cues to action.

AI conversations can reinforce self-efficacy by strengthening the perception that "I can manage this." When an AI chatbot proposes gradual, personalized goals—"Walking 10,000 steps a day might be difficult, but how about starting by walking to the convenience store?"—it creates the conditions for what Bandura [8] termed performance accomplishment, the most powerful source of self-efficacy. Cues to action are equally relevant: because AI conversations are available 24 hours a day, they can function as real-time prompts that encourage behavior "before lying on the sofa after work" or "in anxious moments at dawn." This accessibility complements structural constraints of existing

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Table 1. Correspondence between AI health conversation mechanisms and health promotion theory constructs

AI conversation mechanism	TTM process of change	HBM construct
Deepened self-awareness through AI follow-up questions	Consciousness raising	Perceived susceptibility
Recognizing "I am also at risk" through repeated conversations	Self-reevaluation	Perceived severity
Presentation of specific and gradual behavioral options	Self-liberation	Self-efficacy
24-Hour access and immediate conversation in daily life	-	Cues to action
Shift from information questions to action questions	Contemplation-to-action stage transition	Perceived benefits outweigh perceived barriers

AI, artificial intelligence; HBM, health belief model; TTM, transtheoretical model.

health promotion interventions, such as limited consultation hours and economic, geographic, or psychological barriers to counseling.

These benefits carry cognitive risks. If a user begins with incorrect health assumptions, the chatbot may reinforce them—through echo chamber effects and confirmation bias—and, combined with AI hallucinations, this may solidify erroneous beliefs. The information-to-action question shift I described carries a parallel risk: when driven by flawed premises, it may push users toward harmful behaviors rather than beneficial ones. Future AI systems should incorporate evidence-based nudges that challenge harmful assumptions rather than validate them. AI health conversations should also function as a supplement to, not a replacement for, professional medical consultation, and a human-in-the-loop approach remains critical when AI-generated advice intersects with clinical decision-making.

The correspondence between these AI conversation mechanisms and the constructs of the two theoretical models is summarized in Table 1.

Korean context: intersections with HP2030 (The Fifth National Health Plan)

This discussion connects directly with Korean health promotion policy. The Fifth National Health Plan (HP2030) has established health literacy enhancement as a priority task, with specific action items including the development of health literacy assessment tools, population-specific education systems, and reliable health information delivery systems [9]. The adequate health literacy level among Korean adults is currently estimated at 55%–57% [10].

Here, the health promotion potential of AI health conversations intersects with the goals of HP2030. HP2030 represents a supply-side approach—ensuring that accurate health information is provided to the public. AI health conversations represent a demand-side channel through which consumers independently explore health information and translate it into action. These approaches are complementary. If AI conversations can serve as a mediator that supports not only health information comprehension but also health behavior practice, they may broaden the concept of health literacy itself—from "information comprehension" to "behavior change." Achieving this expansion requires cultivating critical digital health literacy—equipping users not only to access AI-generated health information but to critically evaluate and verify it against professional sources before acting on it.

Korea-specific challenges also exist. Digital literacy gaps and algorithmic biases in AI systems may create new health inequities, disproportionately affecting older adults and lower socioeconomic groups. Systems to verify the accuracy of AI-generated health information remain limited. And the risk of overreliance on AI conversations is real. These factors should be investigated before AI health conversations are promoted as a health promotion tool.

CONCLUSION

AI health conversations have already become part of mainstream health behavior. Systematic reviews and meta-analyses indicate that AI chatbot-based interventions can promote health behavior change, and these effects can be interpreted through core constructs of health promotion theory—the processes of change in TTM and self-efficacy in HBM. This phenomenon warrants study not only as a risk management issue but also as a potential new mediator of health promotion.

We see three research priorities going forward. Randomized controlled trials should test whether open-ended conversations with general-purpose LLMs influence health behavior change. Longitudinal studies should examine whether the information-to-action question shift correlates with TTM stage transitions. And Korea-specific guidelines for AI health conversations—ones that account for digital health equity and safe complementary use—should be developed in conjunction with HP2030's health literacy goals.

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AUTHOR CONTRIBUTIONS

Dr. Sanghyun AHN had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Author reviewed this manuscript and agreed to individual contributions.

Conceptualization: SA. Investigation: SA. Writing–original draft: SA. Writing–review & editing: SA.

CONFLICTS OF INTEREST

The author is the Chief Medical Officer of Mobile Doctor Inc., which operates the Yeolnayo app in Korea, and the Medical Algorithm Director of MoDoc AI Inc., which operates the FeverCoach app in the United States.

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DATA AVAILABILITY

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Predictors of Digital Literacy among Older Adults Living in Urban and Rural Areas

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ABSTRACT

Background: This study examined the factors influencing digital literacy among older adults aged 65 and older, focusing on the roles of social capital and life satisfaction in urban and rural contexts.

Methods: A secondary analysis was conducted using microdata from the Digital Information Gap Survey 2023, a nationally representative dataset collected by the National Information Society Agency. Data from 974 seniors aged 65 or older who have experience using the internet and own a mobile device were analyzed using descriptive statistics. In this study, digital literacy was measured by personal computer use ability and mobile use ability. Pearson's correlation, and hierarchical regression analyses to identify predictors of digital literacy.

Results: Digital literacy was significantly higher in urban areas than in rural areas (t=−5.954, P<0.001). In both settings, younger age, men gender, higher educational attainment, and greater household income were associated with higher digital literacy. Social capital was a significant predictor in urban (β=0.089, P=0.008) and rural (β=0.230, P=0.003) groups, whereas life satisfaction significantly influenced digital literacy only in urban areas (β=0.070, P=0.036). For rural older adults, household type (non–single-person households) was also a significant predictor.

Conclusions: The findings highlight distinct patterns in the determinants of digital literacy between urban and rural older adults. Enhancing social capital and addressing socioeconomic disparities are essential to narrowing the digital divide, particularly in rural areas. Context-sensitive and community-based programs should promote digital inclusion and improve the quality of life among older adults.

Keywords: Digital literacy, Older adults, Social capital, Life satisfaction

INTRODUCTION

In an era of deepening digitalization, the ability to navigate and use digital technologies effectively has become essential for social participation, access to information, and quality of life [1,2]. However, digital literacy remains a significant challenge for older adults aged 65 and above due to diverse cognitive, social, and economic barriers [3,4]. Although the digital divide between generations has been documented adequately, disparities persist within the older adult population, particularly between individuals living in urban and rural areas [5,6]. Understanding the factors influencing digital literacy among older adults is vital for developing policies and interventions that foster meaningful digital engagement.

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Broadly, digital literacy encompasses the ability to access, understand, evaluate, and communicate information through digital media [1]. Digital literacy holds particular importance for older adults, as it enables access to online services, healthcare resources, and social networks, enhancing quality of life and mitigating social isolation [2,7]. Nevertheless, digital literacy among older adults varies widely due to individual and contextual factors [3,4].

Two key influencing factors frequently linked to digital literacy are social capital and life satisfaction. Social capital refers to the resources individuals access through social networks and relationships and is a key determinant of digital literacy [8-10]. Older adults with strong social networks, including family, friends, and community organizations, are more likely to receive support and encouragement in adopting digital technologies [7,9,10]. Urban areas, characterized by more diverse and extensive social networks, offer greater opportunities for digital participation than rural areas, where social ties often remain limited to close-knit communities with fewer technology-related interactions [5,6,11]. Moreover, social capital shapes the motivation and confidence of older adults to learn and use digital tools, influencing their overall digital literacy [8,9].

Life satisfaction, reflecting individuals' general assessment of well-being, is crucial in shaping digital literacy among older adults [8,12]. Individuals reporting higher life satisfaction are more inclined to learn and adopt new digital technologies [12,13]. Conversely, older adults with low life satisfaction, particularly those in rural areas with limited access to social and educational resources, often demonstrate lower digital literacy [5,14]. In addition, it should not be overlooked that in various studies, the mental health satisfaction variable is pointed out as a factor that is correlated with digital literacy [7,8,15,16]. However, in addition to the study that older people with high physical and social satisfaction have easy access to smart media [17], the study of predictive factors for the level of digital information competency also analyzed the effect on the level of digital information competency by selecting life satisfaction as an independent variable [16]. As variables affecting the level of digital utilization ability, a study [15] that analyzes life satisfaction and daily life satisfaction as independent variables by grouping them into physical and mental health variables along with demographic variables can be seen in the same context. Further examination is necessary to understand how social capital and life satisfaction interact to shape digital literacy among older adults, especially across urban and rural contexts [8,14].

A literature review revealed that demographic factors influence the digital literacy of older adults. Mens, those with higher education, younger ages, higher economic status, and those living in multi-person households were found to have higher digital literacy [7,13,15,18,19]. Furthermore, higher life satisfaction among older adults was associated with higher digital information competency [19].

This study investigates the factors influencing digital literacy in adults aged 65 and above, focusing on the roles of social capital and life satisfaction. By comparing urban and rural populations, it aims to offer a more nuanced understanding of the challenges and opportunities older adults face in the digital era. The findings are expected to inform policymakers, educators, and community organizations seeking to promote digital inclusion and enhance the well-being of older adults through targeted interventions and support programs.

METHODS

Study design

This study is a secondary data analysis aimed at determining the predictors of digital literacy among older adults, utilizing a cross-sectional design. The analysis was conducted using data collected from the "Digital Information Gap Survey 2023," a nationwide sample survey.

Subjects

This study utilized microdata from the "Digital Information Gap Survey 2023," administered by the Ministry of Science and ICT and conducted by the National Information Society Agency (NIA). The nationwide survey covered individuals aged 7 and older across 17 cities and provinces, with a specific focus on the digital accessibility and utilization capabilities of information-vulnerable groups, including older adults, persons with disabilities, and low-income individuals. Sampling was performed through a multistage stratified systematic method. Professional interviewers visited target households and conducted face-to-face interviews using a structured questionnaire. The participants comprised 974 individuals aged 65 and above who had experience using the internet.

Measures and scales

The measurement tools used in this study - digital literacy, social capital, and life satisfaction - were developed and utilized in the "Digital Information Gap Survey 2023."

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Digital literacy

Digital literacy was assessed based on personal computer and mobile device usage skills. The survey included seven items evaluating how independently individuals could perform computer-related tasks such as installing and uninstalling software, connecting to and using the internet, configuring web browser settings, connecting external devices, transferring files online, scanning for and removing malware, and creating documents or materials. It also contained seven items evaluating the ability to perform mobile device tasks such as adjusting basic settings, configuring wireless networks, transferring files to a computer, installing and using necessary apps, scanning for and treating malware, and creating documents or materials. Each item was rated on a 4-point scale ranging from 1 "strongly disagree" to 4 "strongly agree," with higher scores indicating greater ability to access and use information through digital devices. This indicator represents a standardized digital competency index developed for the survey, with a Cronbach's α of 0.96 in this study.

Social capital

Social capital was measured using the Internet Social Capital Scales developed by Williams [20], a shortened scale consisting of 10 items on bridging social capital (outward orientation, contact with a wide range of people, being part of a wider world, etc.) and 10 items on bonding social capital (emotional support, access to limited resources, mobilization for solidarity, etc.), with five items each for the bridging and bonding scales. The bridging social capital scale includes the items "Interacting with people makes me feel connected to the larger world," "Interacting with people makes me feel connected to everyone in the world," "I am willing to spend time on community activities," "Interacting with people allows me to talk to new people," and "Interacting always allows me to meet new people." The bonding social capital scale includes items such as "There are people among me who can help me solve my problems," "There are people among me who I can turn to for advice when making very important decisions," "There are people among me with whom I can comfortably talk about intimate personal matters," "There are people among me who I can entrust with important tasks," and "People will help me fight injustice." Each item was rated on a 4-point Likert scale ranging from 1 "strongly disagree" to 4 "strongly agree." The total score was calculated by summing all item responses, with higher scores indicating greater levels of social capital. Cronbach's α for in this study was 0.87.

Life satisfaction

Life satisfaction was assessed through items evaluating respondents' subjective perceptions of their overall life. The scale included five items, such as "I am satisfied with my life" and "I have obtained the important things I desire," rated from 1 "not satisfied at all" to 4 "very satisfied." Higher scores reflected greater overall life satisfaction. Cronbach's α for in this study was 0.81.

General characteristics

Variables identified in previous studies to influence the digital literacy of older adults were set as control variables [7,13,15,16,18,19]. The selected variables were age, gender, education level, whether the elderly live alone, whether they are employed, and average monthly household income. For age and monthly household income, descriptive statistics were presented in categories to aid understanding, and were used as continuous variables in regression analysis. Education level was categorized into less than middle school graduation and higher, and occupation was categorized into employed or unemployed. Average monthly household income was divided into three groups: less than 1 million won, 1 to 3 million won, and 3 million won or more. In the hierarchical regression analysis, it was divided into 11 units from less than 1 million won to 10 million won or more, and was entered as a continuous variable. Urban and rural areas were categorized into cities and counties.

Data collection

The data were collected as part of nationally approved statistics. During the survey, all participants received an explanation of the research purpose and personal information protection, and data collection proceeded only after obtaining their informed consent. This study also entailed a secondary analysis, conducted using publicly available microdata provided by the NIA. The analysis relied solely on non-identifiable data that could not be traced to personal information. This study was a secondary data analysis study utilizing public data and was exempted from review by the Institutional Review Board (IRB) of Incheon Catholic University (IRB review number: 2023-ICCU-IRB-05).

Data analysis

The collected data were analyzed using IBM SPSS Statistics (ver. 26; IRB Corp.). The general characteristics of the participants were examined through descriptive statistics, including frequency, percentage, mean, and standard deviation. Relationships

among variables were analyzed using Pearson's correlation, and hierarchical regression analysis was performed to identify factors influencing digital literacy among older adults.

The regression analysis was conducted in three stages. First, demographic variables such as gender, age, and education level were entered. Second, social capital was added; third, life satisfaction was included to complete the model. The enhancement in the explanatory power of the models was assessed by quantifying the variation (ΔR^2) in the coefficient of determination (R^2) and the statistical significance (*P*-value). Multicollinearity was examined using the Variance Inflation Factor (VIF).

RESULTS

General characteristics of the subjects and key variable characteristics

The mean age of participants was 71.21 years (71.08 urban areas and 72.01 rural areas), with women comprising 52.3% of the sample. The representation of each category was as follows: 56.0% for participants with a middle school education or lower; 80.8% for non–single-person households; 50.4% for those who were employed; and 52.1% for those with a monthly household income between KRW 1 million won and KRW 3 million won. As shown in Table 1, digital literacy levels in urban areas were significantly higher than in rural areas (t=–5.954, *P*<0.001).

Social capital, life satisfaction, and digital literacy of the subjects

Differences in digital literacy according to general characteristics are presented in Table 2, and all variables were statistically significant.

The results of the correlation analysis between key variables by community type are presented in Table 3. In urban areas, social capital was positively correlated with life satisfaction (r=0.36, *P*<0.001) and digital literacy (r=0.21, *P*<0.001). In rural areas, positive correlations were also observed between social capital and life satisfaction (r=0.52, *P*<0.001) and between social capital and digital literacy (r=0.32, *P*<0.001).

Factors affecting digital literacy

This study employed hierarchical regression analysis to examine the influence of community type—urban versus rural—on the digital literacy of older adults.

As presented in Table 4, the regression model for older adults residing in urban areas was statistically significant (F=31.502, *P*<0.001), with a Durbin–Watson statistic of 1.152 and all VIF values below 2. Significant predictors of digital literacy included age (β=–0.081, *P*=0.016), gender (β=0.139, *P*<0.001), educational attainment (β=0.265, *P*<0.001), monthly household income (β=0.169, *P*<0.001), social capital (β=0.089, *P*=0.008), and life satisfaction (β=0.070, *P*=0.036). In summary, digital literacy was higher among younger individuals, men participants, those with at least a high school education, a higher household

Table 1. General characteristics, social capital, life satisfaction and digital literacy of the subjects

Variable	Category	Total (N=974)	Urban areas (n=839)	Rural areas (n=135)	t/χ^2	*P*-value
Age (yr)	<75	798 (81.9)	702 (83.7)	96 (71.1)	12.391	<0.001
	≥75	176 (18.1)	137 (16.3)	39 (28.9)	1.940	0.054
	Mean	71.21±4.86	71.08±4.78	72.01±5.27		
Gender	Men	465 (47.7)	397 (47.3)	68 (50.4)	0.434	0.510
	Women	509 (52.3)	442 (52.7)	67 (49.6)		
Education level	Middle school or lower	545 (56.0)	442 (52.7)	103 (76.3)	26.312	<0.001
	High school or higher	429 (44.0)	397 (47.3)	32 (23.7)		
Household type	Single-person household	187 (19.2)	153 (18.2)	34 (25.2)	3.620	0.057
	Non–single-person household	787 (80.8)	686 (81.8)	101 (74.8)		
Job	Unemployed	483 (49.6)	434 (51.7)	49 (36.3)	11.078	0.001
	Employed	491 (50.4)	405 (48.3)	86 (63.7)		
Monthly household income	Less than 1 million KRW	101 (10.4)	83 (9.9)	18 (13.3)	7.082	0.029
	From 1 million to less than 3 million KRW	508 (52.1)	428 (51.0)	80 (59.3)		
	More than 3 million KRW	365 (37.5)	328 (39.1)	37 (27.4)		
Social capital		2.70±0.49	2.71±0.50	2.65±0.37	–1.631	0.104
Life satisfaction		2.51±0.50	2.52±0.50	2.45±0.49	–1.582	0.114
Digital literacy		1.82±0.67	1.86±0.67	1.53±0.58	–5.954	<0.001

Values are presented as number (%) or mean±standard deviation.
KRW, Korean won.

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Table 2. Comparison of digital literacy according to the general characteristics of the subjects

Variable	Category	Urban areas (n=839)			Rural areas (n=135)		
		Mean±SD	t or F	*P*-value	Mean±SD	t ot F	*P*-value
Age (yr)	<75	1.90±0.67	3.333	0.001	1.67±0.61	5.798	<0.001
	≥75	1.69±0.65			1.20±0.33		
Gender	Men	1.99±0.70	5.388	<0.001	1.70±0.67	−3.466	0.001
	Women	1.75±0.61			1.37±0.42		
Education level	Middle school or lower	1.61±0.59	−12.491	<0.001	1.39±0.45	−4.835	<0.001
	High school or higher	2.14±0.64			2.02±0.69		
Household type	Single-person household	1.66±0.65	−4.192	<0.001	1.39±0.49	−1.912	0.050
	Non–single-person household	1.91±0.66			1.58±0.60		
Job	Unemployed	1.77±0.66	−4.062	<0.001	1.39±0.47	−2.335	0.021
	Employed	1.96±0.66			1.62±0.62		
Monthly household income	Less than 1 million KRW[a]	1.52±0.56	42.994	<0.001	1.17±0.30	19.132	<0.001
	From 1 million to less than 3 million KRW[b]	1.75±0.64		a<b<c	1.42±0.48		a,b<c
	More than 3 million KRW[c]	2.10±0.64			1.96±0.62		

KRW, Korean won; SD, standard deviation.
[a–c]Post hoc test using the Scheffé method.

Table 3. Correlation between social capital, life satisfaction, and digital literacy

	Urban areas (n=839)			Rural areas (n=135)		
	Social capital	Life satisfaction	Digital literacy	Social capital	Life satisfaction	Digital literacy
Social capital	1			1		
Life satisfaction	0.36 (<0.001)	1		0.52 (<0.001)	1	
Digital literacy	0.21 (<0.001)	0.19 (<0.001)	1	0.32 (<0.001)	0.29 (<0.001)	1

Table 4. Factors affecting the digital literacy of older adults in urban areas

	Model 1				Model 2				Model 3			
	B	β	t	*P*	B	β	t	*P*	B	β	t	*P*
Age	−0.012	−0.083	−2.451	0.014	−0.010	−0.075	−2.238	0.025	−0.011	−0.081	−2.407	0.016
Gender (ref.=Women)	0.187	0.140	4.176	<0.001	0.190	0.142	4.262	<0.001	0.185	0.139	4.158	<0.001
Education level (ref.=Middle school or lower)	0.372	0.279	8.003	<0.001	0.357	0.268	7.712	<0.001	0.353	0.265	7.628	<0.001
Household type (ref.=Single-person household)	−0.030	−0.018	−0.515	0.606	−0.034	−0.020	−0.581	0.561	−0.041	−0.024	−0.697	0.486
Job (ref.=Unemployed)	0.009	0.007	0.187	0.852	0.011	0.008	0.241	0.810	0.013	0.010	0.290	0.772
Monthly household income	0.075	0.197	5.140	<0.001	0.068	0.179	4.662	<0.001	0.064	0.169	4.377	<0.001
Social capital					0.149	0.112	3.567	<0.001	0.118	0.089	2.674	0.008
Life satisfaction									0.093	0.070	2.105	0.036
F (*P*)	38.432 (<0.001)				35.223 (<0.001)				31.502 (<0.001)			
R^2 (Adj. R^2)	0.217 (0.212)				0.229 (0.223)				0.233 (0.226)			

Adj., adjusted; ref., reference.

income, greater social capital, and higher life satisfaction.

As shown in Table 5, the regression model analyzing predictors of digital literacy among older adults residing in rural areas was statistically significant (F=14.253, *P*<0.001), with a Durbin–Watson statistic of 1.336 and all VIF values below 2. Significant predictors of digital literacy included age (β=–0.205, *P*=0.008), gender (β=0.176, *P*=0.018), education level (β=0.295, *P*<0.001), household type (β=–0.224, *P*=0.005), monthly household income (β=0.332, *P*<0.001), and social capital (β=0.230, *P*=0.003). In summary, digital literacy was higher among younger individuals, mens, those with at least a high school education, non–single-person households, individuals with higher monthly household income, and those with greater social capital.

DISCUSSION

This study examined factors influencing the digital literacy of

Table 5. Factors affecting the digital literacy of older adults in rural areas

	Model 1				Model 2				Model 3			
	B	β	t	*P*	B	β	t	*P*	B	β	t	*P*
Age	−0.027	−0.243	−3.076	0.003	−0.023	−0.211	−2.792	0.006	−0.023	−0.205	−2.690	0.008
Gender (ref.=Women)	0.210	0.181	2.361	0.020	0.206	0.178	2.445	0.016	0.203	0.176	2.399	0.018
Education level (ref.=Middle school or lower)	0.395	0.290	3.901	<0.001	0.401	0.295	4.169	<0.001	0.401	0.295	4.168	<0.001
Household type (ref.=Single-person household)	−0.259	−0.194	−2.383	0.019	−0.298	−0.224	−2.875	0.005	−0.298	−0.224	−2.870	0.005
Job (ref.=Unemployed)	0.005	0.004	0.057	0.954	−0.005	−0.004	−0.057	0.955	−0.004	−0.003	−0.042	0.966
Monthly household income	0.161	0.337	4.000	<0.001	0.161	0.337	4.217	<0.001	0.159	0.332	4.132	<0.001
Social capital					0.397	0.254	3.866	<0.001	0.358	0.230	3.021	0.003
Life satisfaction									0.059	0.050	0.652	0.516
F (*P*)	14.904 (<0.001)				16.302 (<0.001)				14.253 (<0.001)			
R^2 (Adj. R^2)	0.411 (0.384)				0.473 (0.444)				0.475 (0.442)			

Adj., adjusted; ref., reference.

adults aged 65 and above, focusing on how social capital and life satisfaction affected digital literacy across urban and rural communities. The analysis showed that age, gender, education level, household income, social capital, and life satisfaction were significant predictors of digital literacy overall. However, the strength and direction of some of these factors varied depending on community type [3,4,21].

In urban and rural areas, digital literacy was higher among younger individuals, mens, those with at least a high school education, and those with higher household income. This finding reinforces that a digital divide persists even within the older adult population, a conclusion consistently supported by previous studies [3-6]. It also highlights the importance of education and economic resources as fundamental components of digital literacy [3,21]. In rural areas, non-single-household status was an additional significant predictor—the presence of family members or cohabitants may provide practical help or emotional encouragement for digital technology use [7,9].

Social capital was a significant predictor of digital literacy in urban and rural settings. Its influence was particularly strong among older adults in rural areas—relationship-based social support is critical in bridging the information gap in regions with lower digital accessibility [8-11]. These findings are consistent with prior research demonstrating that social capital facilitates the adoption of digital technology [8-10]. In rural areas, offline community networks appear especially effective, and their use in disseminating information or designing technical training programs can be equally beneficial [11,22].

Life satisfaction was a significant predictor of digital literacy among older adults in urban areas, but did not reach statistical significance among those in rural areas. This result aligns with previous research, which suggests that life satisfaction influences individuals' interest in, attitudes toward, and willingness to engage with digital technology, as well as their readiness to embrace new challenges, although this effect may depend on regional context [12-14]. As social capital and physical factors such as household type and income exert a stronger influence on digital competency than life satisfaction among older adults in rural areas, the context-dependent and potentially diminished role of life satisfaction in technology adoption should be considered [5,11,14,21].

This study empirically demonstrated a clear disparity in digital literacy levels between urban and rural areas—older adults in rural areas had significantly lower average digital literacy than those in urban areas. This finding reinforces the spatial inequality repeatedly highlighted in previous research on the digital divide, suggesting that disparities in the distribution of physical infrastructure and social and emotional resources affect digital capabilities [5,6,11,14]. Moreover, the results indicate that older adults living in rural areas tend to have lower educational attainment, lower household income, and a higher proportion of single-person households, reflecting structural barriers that limit access to and use of digital technology [5,6,11].

Although our descriptive statistics did not reveal significant mean differences in life satisfaction and social capital between urban and rural areas, prior research suggests that social capital is not a unidimensional construct; rural areas tend to have stronger bonding social capital while urban areas may exhibit greater bridging social capital, which could result in comparable average levels when measured without considering compositional differences [22]. Furthermore, the impact of social capital on subjective well-being has been shown to vary across geographic contexts, potentially due to differences in community associations, infrastructure, and socio-economic conditions

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[23].

The findings of this study underscore the need for more nuanced, locally tailored intervention strategies to promote digital inclusion among older adults. For those living in urban areas, implementing motivation-enhancing programs that improve life satisfaction and foster autonomous technology learning may be an effective approach [12,13]. For older adults in rural areas, technology education delivered through community-based initiatives, supported by social capital and strengthened by family and local networks, is essential [9,11,22]. In these settings, digital literacy programs should aim to build technical skills and enhance social connectedness and overall life satisfaction [2,7,9,12,13].

As this study was conducted through secondary data analysis, it has some limitations related to variable composition and the depth of measurement items. In particular, the study did not capture the detailed components of social capital (e.g., trust, reciprocity, and participation) with sufficient precision. Moreover, the cross-sectional design precludes definitive conclusions about causality. Future research should employ longitudinal designs or incorporate qualitative approaches to provide a more comprehensive understanding of the processes underlying the development of digital competencies among older adults.

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AUTHOR CONTRIBUTIONS

Dr. Hyunjung MOON had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Author reviewed this manuscript and agreed to individual contributions.

Conceptualization, data curation, writing–original draft, reviewing & editing: HM.

CONFLICTS OF INTEREST

No existing or potential conflict of interest relevant to this article was reported.

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DATA AVAILABILITY

The data presented in this study are available upon reasonable request from the corresponding author.

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Sex Differences in the Modifying Effect of Diabetes on the Exercise–Grip Strength Relationship: Korea National Health and Nutrition Examination Survey (2017–2019)

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ABSTRACT

Background: Handgrip strength (HGS) is an indicator of late-life health, associated with disability, cardiovascular and all-cause mortality. While exercise helps maintain HGS, diabetes may reduce its benefits. This study investigated the association between exercise and low HGS (LHGS) stratified by diabetes status and sex.

Methods: Data from 16,443 participants in the 2017–2019 Korea National Health and Nutrition Examination Survey were analyzed. HGS was measured using a digital dynamometer. Exercise type and frequency were assessed by questionnaire. Three-way and two-way interaction terms were analyzed for exercise, sex and diabetes.

Results: Aerobic exercise, resistance exercise, and diabetes were significantly associated with LHGS (P<0.05). A significant interaction between diabetes and aerobic exercise was observed in females (odds ratio [OR] of LHGS=1.704, 95% confidence interval=1.073–2.707). Among males, both exercise types were associated with lower odds of LHGS regardless of diabetes status, except for aerobic exercise in non-diabetic males. Among males, the ORs of LHGS for aerobic and resistance exercise were 0.479 (0.278–0.827) and 0.317 (0.165–0.611) with diabetes, 0.757 (0.554–1.035) and 0.536 (0.360–0.798) without diabetes. Among females, the ORs of LHGS for aerobic exercise and resistance exercise were 1.109 (0.716–1.719) and 0.529 (0.224–1.249) with diabetes, 0.676 (0.539–0.848) and 0.795 (0.564–1.121) without diabetes.

Conclusions: The modifying effect of diabetes on the relationship between exercise and grip strength was observed in females but not in males. Females with diabetes may require tailored exercise guideline to prevent LHGS.

Keywords: Diabetes mellitus, Hand strength, Physical fitness, Exercise, Resistance training

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INTRODUCTION

Handgrip strength (HGS) is a prognostic marker for future disability in older adults who are not yet disabled [1]. It has also been identified as a predictor of cardiovascular and all-cause mortality, including outcomes such as myocardial infarction and stroke [2,3]. HGS typically peaks between the ages of 29 and 39 and declines progressively with age [4]. A population-based study in Korea reported that approximately 32% of males and 33% of females aged 65 years or older exhibited low HGS (LHGS) [5]. Notably, significant sex-related differences have been observed, with males consistently demonstrating higher HGS than females [4].

Exercise is a well-established method for maintaining grip strength in older adults. A cross-sectional study found that elderly individuals who engaged in either aerobic or resistance exercise had significantly higher grip strength, with the greatest benefits observed when both exercise types were combined [6]. Aerobic activities, such as cycling, have also been shown to be as effective as resistance training in increasing skeletal muscle mass [7].

Moreover, the effects of exercise appear to differ by sex. A systematic review of prospective trials on exercise intervention reported that increase in upper and lower body strength and cardiorespiratory fitness was more significant in males while motor fitness, such as agility, balance, and speed, was more improved in females [8].

Type 2 diabetes, characterized by hyperglycemia, hyperinsulinemia and insulin resistance, is related with muscle atrophy and reduced strength in elderly population. According to a longitudinal study, elderly people with type 2 diabetes had accelerated reduction of leg muscle mass and strength compared with age matched healthy counterparts [9]. Cross-sectional study also showed that people with diabetes had significantly lower grip strength compared to those without the condition [10]. Moreover, when participating in the same resistance training program, individuals with diabetes tended to show smaller gains in muscle strength [11].

The pathophysiology of the detrimental effect of diabetes on muscle is complex. According to a research, peripheral neuropathy, a complication of diabetes, was associated with leg weakness [12]. An interventional study found that people with type 2 diabetes had impaired peak exercise performance compared to healthy age-matched controls [13]. Its follow up study found that sex difference in the effect of diabetes existed; females with diabetes were compared with healthy counterparts and had greater reduction in peak exercise performance than the group between males with diabetes and their counterparts.

Previous studies show grip strength is related to sex, diabetes, and exercise. There remains gap of evidence whether diabetes influences the association between exercise and HGS and whether there is sex difference as well. By analyzing Korean nationwide population based survey and examination data, the authors sought to find the correlation.

METHODS

Study design and subjects

This study utilized data from the Korean National Health and Nutrition Examination Survey (KNHANES), collected between 2017 and 2019. Conducted annually by the Korean government, KNHANES gathers nationally representative information on health status, nutritional intake, and laboratory values through structured questionnaires and physical examinations [14]. Of the 24,229 participants surveyed during this period, individuals who were under 19 years of age (4,616 participants) or lacked HGS measurements (1,423 participants) were excluded. Then nonresponders for the questionnaire determining diabetes (1,029 participants), exercise (718 participants) were excluded. A total of 16,443 participants were included in the final analysis.

This study was approved by the Institutional Review Board (IRB) of Seoul National University Bundang Hospital (IRB No: X-2511-1007-902). The requirement for informed consent was waived by the IRB because the study was a secondary analysis of de-identified, publicly available data from the KNHANES 2017–2019.

Variables

HGS was assessed using a digital grip strength dynamometer (T.K.K 5401; Takei Scientific Instruments Co., Ltd). It was measured with both hands and three trials were given for each hand. The maximum recorded value was used as the final grip strength. LHGS was defined based on the Asian Working Group for Sarcopenia (AWGS) 2019 criteria: <28 kg for males and <18 kg for females [15].

Aerobic and resistance exercise were assessed based on a cut-off value using the global recommendations on physical activity for health from World Health Organization [16]. Aerobic exercise was defined as a 150-minute physical activity with moderate intensity or a 75-minute physical activity with high intensity

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per week, or an equivalent combination per week. Resistance exercise was defined as engaging in weight training or strength training more than once a week.

Additional variables collected from the survey included body mass index (BMI), alcohol consumption, smoking status, household income, education level, and comorbidities. Obesity was defined using the Asia-Pacific BMI cut-off point of ≥25 kg/m^2 [17]. Alcohol drinkers were defined as individuals who consumed any alcohol in the previous year. Household income was represented in quartiles, with the 1st quartile group representing the lowest income group and the 4th quartile group the highest. Comorbidities, such as hypertension, angina, myocardial infarction, and chronic obstructive pulmonary disease (COPD), were considered present if participants reported having been diagnosed by a physician. Among comorbidity, the arthritis was treated as a separate variable. Diabetes was defined as having been diagnosed by a doctor, or based on laboratory criteria: glycated hemoglobin (HbA1c)≥48 mmol/mol, fasting blood glucose≥7mmol/L, or current use of diabetes medications, including insulin.

Data analysis

Bivariate logistic regression was used to assess relationships between LHGS and baseline demographic variables. For the relationship between each type of exercise and LHGS, multivariate logistic regression was performed with an adjustment for confounders. There were significant missing values for the comorbidity COPD (n=4,722). The baseline characteristics was analyzed for the subgroup with missing value for COPD and is added as the Supplementary Table 1. Compared with the baseline participants, this group's participants were younger (mean age, 47.0 years vs. 30.4 years), had similar proportion of males (50.1% vs. 53.0%), did more aerobic exercise (46.2% vs. 56.1%), did similar resistance exercise (22.8% vs. 26.1%), had higher education level and had less diabetes (10.9% vs. 2.3%).

Because exercise, diabetes, and sex may jointly influence HGS, three-way and two-way interaction terms were prespecified primary analyses. Then, the participants were stratified by diabetes status and sex, and the relationship between exercise and LHGS was assessed. All of the data was handled with a complex survey design. STATA version 16.0 (Stata Corp.) was used for analysis, in which statistical significance was agreed with *P*-value <0.05.

RESULTS

Table 1 shows the demographic characteristics of participants included in the final analysis and stratified by sex and diabetes. Among the 16,443 participants, 7,308 were males and 9,149 were females. Since this study was based on a complex survey, these participants represented 37,528,400 persons. In both sexes, the weighted mean age was higher for those with diabetes than their counterparts. The mean HGS was greater in males and females without diabetes and they also exercised more, in terms of both aerobic and resistance exercise. The prevalence of diabetes was 10.9%. The proportion of LHGS is 8.8% for males with diabetes, 4.8% for males without diabetes, 25.4% for females with diabetes, and 10.2% for females without diabetes.

All variables—age, obesity, alcohol consumption, smoking, household income, education level and comorbidity—were associated with LHGS in bivariate analysis and were considered as covariates except exercise and diabetes. In both sexes, aerobic exercise and resistance exercise were related to low prevalence of LHGS, while diabetes was related to high prevalence of LHGS (Table 2).

A multivariate logistic regression was fit to examine the three-way interaction of exercise, sex, and diabetes. The analysis revealed a statistically significant three-way interaction between aerobic exercise, diabetes and sex (odds ratio [OR] of LHGS=2.350, 95% confidence interval [95% CI]=1.119–4.932) (Table 3). Then, two-way interaction of exercise and diabetes was further analyzed by stratifying sex. The results showed that for males, the interaction between exercise and diabetes was not statistically significant, whereas for females, the interaction between aerobic exercise and diabetes was with OR of LHGS=1.704 and 95% CI=1.073–2.707 (Table 4).

Subgroup analyses by diabetes status and sex are presented in Table 5. Overall protective effects of exercise were analyzed. The data showed that for males, aerobic and resistance exercise had lower LHGS OR (aerobic, OR of LHGS=0.696 [95% CI=0.535–0.908]; resistance, OR of LHGS=0.488 [95% CI=0.348–0.683]). In females's case, aerobic exercise had smaller OR for LHGS, but resistance exercise had no significance (aerobic, OR of LHGS=0.744 [95% CI=0.609–0.909]; resistance, OR of LHGS=0.743 [95% CI=0.541–1.021]). Then, protective effects of exercise according to diabetes presence were analyzed. Aerobic exercise in diabetic males was associated with low odds of LHGS, significantly, while it was non-significantly associated in non-diabetic males (diabetic, OR of LHGS=0.479

Table 1. Demographic characteristics of the study subjects

Characteristic	Total	Male		Female	
		Diabetes	Non-diabetes	Diabetes	Non-diabetes
No. of subjects (population)[a]	16,443 (37,528,400)	1,132 (2,333,747.6)	6,176 (16,480,956)	1,006 (1,745,515.8)	8,143 (16,968,180)
Age (yr)	47.0±0.2	58.1±0.5	44.3±0.3	63.3±0.6	46.5±0.3
Body mass index (kg/m^2)	23.9±0.0	25.6±0.1	24.4±0.1	25.8±0.2	23.0±0.1
Obesity, %[b]	34.6±0.5	53.3±1.7	40.2±0.7	53.0±1.9	24.7±0.6
Handgrip strength (kg)	32.1±0.1	37.9±0.3	40.9±0.1	21.5±0.2	23.8±0.1
Low handgrip strength, %[c]	8.4±0.3	8.8±0.8	4.8±0.3	25.4±1.6	10.2±0.5
Alcohol drinker, %[d]	59.0±0.5	70.3±1.7	72.4±0.7	24.7±1.7	47.8±0.7
Smoking status					
Current smoker, %	20.8±0.5	34.9±1.8	35.7±0.8	3.4±0.7	6.1±0.4
Past smoker, %	22.3±0.4	48.2±1.8	36.6±0.7	3.6±0.6	6.7±0.3
Aerobic exerciser, %[e]	46.2±0.6	39.4±1.8	51.4±0.8	33.9±1.9	43.3±0.7
Resistance exerciser, %[f]	22.8±0.4	24.6±1.6	31.4±0.7	9.3±1.1	15.5±0.5
Household income (quartile)					
1 (lowest), %	14.4±0.5	21.6±1.4	10.8±0.5	35.3±2.0	14.8±0.6
2, %	24.0±0.6	26.8±1.5	22.9±0.8	27.8±1.6	24.2±0.7
3, %	29.0±0.6	26.4±1.6	30.9±0.8	20.6±1.5	28.5±0.7
4 (highest), %	32.6±0.8	25.1±1.6	35.5±1.0	16.3±1.5	32.4±0.9
Education level					
≤Elementary school, %	12.9±0.5	17.0±1.2	6.7±0.4	48.0±1.9	14.7±0.6
Middle school, %	8.2±0.3	15.1±1.2	7.0±0.4	15.8±1.5	7.7±0.4
High school, %	35.4±0.6	37.4±1.8	37.4±0.8	25.4±1.7	34.1±0.7
≥University, %	43.5±0.8	30.5±1.8	49.0±1.0	10.8±1.2	43.4±0.9
Comorbidity, %	31.6±0.6	56.1±1.8	29.4±0.9	62.9±1.8	23.7±0.7
Hypertension, %	19.2±0.5	50.1±1.9	15.7±0.6	58.8±1.9	14.3±0.5
Angina, MI, %	2.0±0.1	6.9±0.8	2.1±0.2	4.1±0.6	1.1±0.1
COPD, %	0.5±0.1	0.5±0.2	0.7±0.2	0.4±0.3	0.3±0.1
Diabetes, %	10.9±0.3				
Arthritis, %	9.5±0.3	7.4±0.9	3.6±0.2	33.7±1.8	13.0±0.4

Continuous variables are presented as weighted mean±standard error (SE), and categorical variables as weighted percentage±SE.
COPD, chronic obstructive pulmonary disease; MI, myocardial infarction.
[a]The number of subjects represents the unweighted sample size; values in parentheses indicate the weighted population. [b]Body mass index≥25 kg/m^2. [c]Used Asian Working Group for Sarcopenia 2019 consensus reference, low handgrip strength is defined as <28 kg for male, and <18 kg for female. [d]Ever drunk in his/her lifetime & drunk in the previous year. [e]Performed more than 150 minutes of moderate intensity physical activity or 75 minutes of high intensity activity per week, or a combination of both. [f]Performed more than 1 day of resistance activity in a week.

[95% CI=0.278–0.827]; non-diabetic, OR of LHGS=0.757 [95% CI=0.554–1.035]). In contrast, aerobic exercise in diabetic females was non-significantly associated with LHGS, while it was significantly associated in non-diabetic females (diabetic, OR of LHGS=1.109 [95% CI=0.716–1.719]; non-diabetic, OR of LHGS=0.676 [95% CI=0.539–0.848]). Resistance exercise in males was significantly associated with smaller odds of LHGS, regardless of diabetes status (diabetic, OR of LHGS=0.317 [95% CI=0.165–0.611]; non-diabetic, OR of LHGS=0.536 [95% CI]=0.360–0.798). On the other hand, resistance exercise in females was not significant, regardless of diabetes status (diabetic, OR of LHGS=0.529 [95% CI=0.224–1.249]; non-diabetic, OR of LHGS=0.795 [95% CI=0.564–1.121]).

DISCUSSION

This study reveals important insights into the relationship between physical activity and grip strength, particularly in the context of diabetes status. Our key finding was the significant two-way interaction between aerobic exercise and LHGS among females and not males. Also, the association of aerobic exercise and LHGS was significant in females without diabetes, but not with diabetes. In males, aerobic exercise was significant for diabetics and insignificant for non-diabetics. Resistance exercise was significant for males with or without diabetes and insignificant for females with or without diabetes.

Results of this study are consistent with previous research demonstrating the beneficial impact of exercise on maintain-

Table 2. Factors associated with low handgrip strength

Variable	Total				Male				Female			
	n/N (%)[a]	OR[b]	95% CI	*P*-value	n/N (%)[a]	OR[b]	95% CI	*P*-value	n/N (%)[a]	OR[b]	95% CI	*P*-value
Age		1.061	1.053–1.068	<0.001		1.066	1.053–1.079	<0.001		1.056	1.049–1.064	<0.001
Obesity												
No	10,722/16,394 (65.4)	1			4,242/7,289 (58.2)	1			6,619/9,105 (72.7)	1		
Yes	5,672/16,394 (34.6)	0.771	0.677–0.878	<0.001	3,047/7,289 (41.8)	0.487	0.381–0.623	<0.001	2,486/9,105 (27.3)	1.204	1.032–1.405	0.018
Alcohol consumption												
Non drinker	6,734/16,424 (41.0)	1			2,028/7,295 (27.8)	1			4,957/9,129 (54.3)	1		
Current drinker	9,690/16,424 (59.0)	0.337	0.296–0.384	<0.001	5,267/7,295 (72.2)	0.348	0.281–0.432	<0.001	4,172/9,129 (45.7)	0.425	0.355–0.508	<0.001
Smoking												
Non smoker	9,342/16,418 (56.9)	1			1,925/7,293 (26.4)	1			8,012/9,125 (87.8)	1		
Current smoker	3,415/16,418 (20.8)	0.398	0.328–0.484	<0.001	2,596/7,293 (35.6)	0.698	0.518–0.942	0.019	529/9,125 (5.8)	0.577	0.403–0.824	0.003
Past smoker	3,661/16,418 (22.3)	0.575	0.495–0.669	<0.001	2,771/7,293 (38.0)	1.080	0.843–1.383	0.542	584/9,125 (6.4)	0.631	0.448–0.889	0.009
Aerobic exerciser												
No	8,846/16,443 (53.8)	1			3,659/7,303 (50.1)	1			5,265/9,140 (57.6)	1		
Yes	7,597/16,443 (46.2)	0.517	0.452–0.591	<0.001	3,644/7,303 (49.9)	0.487	0.386–0.614	<0.001	3,875/9,140 (42.4)	0.577	0.494–0.674	<0.001
Resistance exerciser												
No	12,694/16,443 (77.2)	1			5,068/7,303 (69.4)	1			7,778/9,140 (85.1)	1		
Yes	3,749/16,443 (22.8)	0.407	0.332–0.498	<0.001	2,235/7,303 (30.6)	0.427	0.309–0.589	<0.001	1,362/9,140 (14.9)	0.529	0.407–0.687	<0.001
Household income (quartile)												
1	2,361/16,394 (14.4)	1			882/7,285 (12.1)	1			1,521/9,109 (16.7)	1		
2	3,935/16,394 (24.0)	0.299	0.253–0.354	<0.001	1,705/7,285 (23.4)	0.316	0.245–0.407	<0.001	2,241/9,109 (24.6)	0.302	0.245–0.373	<0.001
3	4,754/16,394 (29.0)	0.208	0.173–0.250	<0.001	2,207/7,285 (30.3)	0.150	0.109–0.207	<0.001	2,532/9,109 (27.8)	0.263	0.214–0.323	<0.001
4	5,344/16,394 (32.6)	0.171	0.141–0.207	<0.001	2,491/7,285 (34.2)	0.130	0.091–0.185	<0.001	2,815/9,109 (30.9)	0.212	0.170–0.264	<0.001
Education level												
≤Elementary school	2,119/16,429 (12.9)	1			576/7,297 (7.9)	1			1,626/9,132 (17.8)	1		
Middle school	1,347/16,429 (8.2)	0.322	0.260–0.399	<0.001	584/7,297 (8.0)	0.402	0.290–0.557	<0.001	776/9,132 (8.5)	0.315	0.242–0.411	<0.001
High school	5,816/16,429 (35.4)	0.158	0.134–0.185	<0.001	2,729/7,297 (37.4)	0.169	0.130–0.219	<0.001	3,041/9,132 (33.3)	0.177	0.145–0.215	<0.001
≥University	7,147/16,429 (43.5)	0.108	0.089–0.130	<0.001	3,408/7,297 (46.7)	0.088	0.065–0.120	<0.001	3,689/9,132 (40.4)	0.142	0.112–0.179	<0.001
Comorbidity												
No	8,144/11,907 (68.4)	1			3,405/5,182 (65.7)	1			4,775/6,725 (71.0)	1		
Yes	3,763/11,907 (31.6)	2.570	2.254–2.929	<0.001	1,777/5,182 (34.3)	2.279	1.799–2.887	<0.001	1,950/6,725 (29.0)	3.051	2.602–3.577	<0.001
Arthritis												
No	14,881/16,443 (90.5)	1			7,004/7,303 (95.9)	1			7,778/9,140 (85.1)	1		
Yes	1,562/16,443 (9.5)	3.824	3.337–4.384	<0.001	299/7,303 (4.1)	3.719	2.751–5.028	<0.001	1,362/9,140 (14.9)	3.051	2.613–3.561	<0.001
Diabetes												
No	14,651/16,443 (89.1)	1			6,397/7,303 (87.6)	1			8,290/9,140 (90.7)	1		
Yes	1,792/16,443 (10.9)	2.328	2.022–2.682	<0.001	906/7,303 (12.4)	1.918	1.533–2.401	<0.001	850/9,140 (9.3)	3.013	2.510–3.616	<0.001
Moderate to vigorous exercise												
1st quartile	2,550/10,946 (23.3)	1			967/4,912 (19.7)	1			1,623/6,034 (26.9)	1		
2nd quartile	2,682/10,946 (24.5)	0.875	0.711–1.076	0.204	1,076/4,912 (21.9)	0.632	0.420–0.951	0.028	1,647/6,034 (27.3)	1.012	0.784–1.305	0.928
3rd quartile	2,769/10,946 (25.3)	0.644	0.511–0.811	<0.001	1,233/4,912 (25.1)	0.522	0.339–0.804	0.003	1,539/6,034 (25.5)	0.759	0.587–0.981	0.035
4th quartile	2,945/10,946 (26.9)	0.442	0.340–0.575	<0.001	1,636/4,912 (33.3)	0.484	0.314–0.746	0.001	1,225/6,034 (20.3)	0.510	0.373–0.699	<0.001

Values are presented as weighted percentage for categorical variables. The number of subjects represents the unweighted sample size.
[a]The denominators vary due to missing data. [b]Odds ratio (OR), 95% confidence interval (95% CI), and *P*-values are calculated using bivariate analysis.

Table 3. Three-way interaction analysis of exercise, sex, diabetes on the ORs for LHGS

Variable	For aerobic exercise			For resistance exercise		
	OR[a]	95% CI	*P*-value	OR[a]	95% CI	*P*-value
Exercise	0.685	0.508–0.923	0.013	0.528	0.362–0.771	<0.001
Diabetes	1.264	0.924–1.729	0.143	1.236	0.934–1.635	0.138
Sex	1.549	1.162–2.065	0.003	1.411	1.076–1.851	0.013
Exerciser^diabetes	0.747	0.406–1.373	0.346	0.610	0.287–1.294	0.197
Exerciser^sex	1.002	0.689–1.455	0.994	1.542	0.908–2.617	0.109
Diabetes^sex	0.819	0.539–1.244	0.348	0.994	0.683–1.447	0.975
Exerciser^diabetes^sex	2.350	1.119–4.932	0.024	1.139	0.336–3.863	0.834

CI, confidence interval; LHGS, low handgrip strength; OR, odds ratio.
[a]By multivariate logistic regression adjusted for quadratic age, obesity, alcohol consumption, smoking, household income, education, comorbidity, arthritis, and three-way interaction between exercise, sex, and diabetes.

Table 4. Two-way interaction analysis of exercise type and diabetes stratified by sex on the ORs for LHGS

Variable		Male			Female		
		OR[a]	95% CI	*P*-value	OR[a]	95% CI	*P*-value
Aerobic exercise	Exerciser	0.794	0.560–1.044	0.091	0.669	0.533–0.839	0.001
	Diabetes	1.217	0.862–1.717	0.265	1.093	0.839–1.423	0.509
	Exerciser^diabetes	0.667	0.347–1.281	0.223	1.704	1.073–2.707	0.024
Resistance	Exerciser	0.551	0.371–0.819	0.003	0.786	0.557–1.110	0.171
	Diabetes	1.162	0.850–1.587	0.345	1.290	1.026–1.623	0.030
	Exerciser^diabetes	0.586	0.259–1.247	0.158	0.676	0.268–1.702	0.405

CI, confidence interval; LHGS, low handgrip strength; OR, odds ratio.
[a]By multivariate logistic regression adjusted for quadratic age, obesity, alcohol consumption, smoking, household income, education, comorbidity, arthritis and interaction between exercise and diabetes.

Table 5. Association between LHGS and type of exercise in relation to diabetes and sex

Variable		Male			Female		
		OR[a]	95% CI	*P*-value	OR[a]	95% CI	*P*-value
Aerobic exerciser	Overall	0.696	0.535–0.908	0.007	0.744	0.609–0.909	0.004
	Diabetes (+)	0.479	0.278–0.827	0.008	1.109	0.716–1.719	0.642
	Diabetes (–)	0.757	0.554–1.035	0.081	0.676	0.539–0.848	0.001
Resistance exerciser	Overall	0.488	0.348–0.683	<0.001	0.743	0.541–1.021	0.067
	Diabetes (+)	0.317	0.165–0.611	0.001	0.529	0.224–1.249	0.146
	Diabetes (–)	0.536	0.360–0.798	0.002	0.795	0.564–1.121	0.191

CI, confidence interval; LHGS, low handgrip strength; OR, odds ratio.
[a]By multivariate logistic regression adjusted for quadratic age, obesity, alcohol consumption, smoking, household income, education, comorbidity, and arthritis.

ing adequate grip strength. For instance, a British longitudinal cohort study reported that mid-life exercise (ages 40–50 years) was significantly associated with a lower OR for LHGS in early 60s [18]. Similarly, a Korean cross-sectional study found that elderly individuals who exercised regularly had a lower prevalence of LHGS compared to non-exercisers [6]. Our study corroborates these findings, further supporting the general protective effects of both aerobic and resistance exercise on HGS.

As mentioned before, data shows a significant interaction between aerobic exercise and diabetes in females, but not males. Such effect may be due to sex difference in muscle mass that is product of lifetime levels of endogenous sex hormone. Evidence shows that testosterone supplement increased muscle mass in both males and females [19,20].

Another finding is that only aerobic exercise in non-diabetic females was associated with low odds of LHGS. Prior studies suggested that individuals with diabetes had lower aerobic capacity, measured by peak oxygen consumption and maximal walking time [13]. Moreover, when comparing with their non-diabetic counterparts, females with diabetes showed more pronounced decline in cardiorespiratory fitness than males with diabetes [21]. Consequently, even when females with diabetes

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report meeting exercise guidelines, the intensity or physiological load may not be sufficient to increase strength. This suggests that current exercise recommendations may need to be adjusted for this subgroup, potentially emphasizing greater duration or intensity to maintain grip strength.

Interestingly, in males, the association between ORs of LHGS and aerobic exercise was significant in males with diabetes but not in without diabetes. This could be due to small sample size after stratification. The sample size of males with diabetes was 1,132 and those that participate in aerobic exercise was 39.4%, 446 participants. The sample size of males without diabetes was 6,176 and those that participate in aerobic exercise was 51.4%, 3,174 participants. In males without diabetes, the OR of LHGS for aerobic exercise was 0.75 with *P*-value of 0.081 and the upper limit of 95% CI of 1.035, which was marginally above "1." The process of stratification and reducing subgroup sample size, males without diabetes, could have reduced the strength of association between aerobic exercise and OR of LHGS.

Furthermore, association between resistance exercise and ORs of LHGS was significant in males but not in females. The OR of LHGS for resistance exercise in females was 0.743 and the upper limit of 95% CI was 1.021, which was marginally above "1." These values were similar to the corresponding values for aerobic exercise in the same sex; 0.744 and 0.909. This difference in significance can be explained by the small sample size that participated in resistance exercise in females. According to Table 2, sample size that accounted for males participating in resistance exercise was 2,235 out of 7,303 (30.6%). This size in females was 1,362 out of 9,140 (14.9%). Since there was small number of females participating in resistance exercise compared to males, the association may not have reached statistical significance.

Despite these valuable insights, our study has several limitations. As a cross-sectional study, it is inherently limited in establishing causal relationships. We cannot definitively determine whether exercise reduces LHGS or if LHGS, conversely, limits an individual's ability to engage in exercise. Future longitudinal and interventional studies are crucial to clarify this directionality. Additionally, several key variables, including exercise habits and smoking status, were collected via self-answered questionnaires. While this method carries the potential for reporting bias, it's important to note that the Global Physical Activity Questionnaire, utilized for assessing exercise type and amount, has been validated for predicting actual exercise practice [22]. Similarly, numerous studies have demonstrated the accuracy of self-reported smoking status [23], which somewhat mitigates concerns about bias in this particular variable.

SUPPLEMENTARY MATERIAL

Supplementary Table 1. Comparison of demographic characteristics of the included participants and subgroup with missing values

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Dr. Woo Kyung BAE had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. All authors reviewed this manuscript and agreed to individual contributions.

Conceptualization: JHJ and WKB. Data curation: JHJ. Formal analysis: JHJ and WKB. Investigation: SML. Methodology: EC, SP, HL, and WKB. Project administration: WKB. Writing–original draft: JHJ. Writing–review & editing: SML, EC, SP, HL, and WKB.

CONFLICTS OF INTEREST

No existing or potential conflict of interest relevant to this article was reported.

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DATA AVAILABILITY

The data presented in this study are available at https://www.kdca.go.kr/.

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Effects of Upper-Extremity Heat Stress Combined with Resistance Training on Skill and Basal Fitness, Isokinetic Muscle Strength, and Anabolic Hormones in Wheelchair Rugby Athletes with Spinal Cord Injury

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ABSTRACT

Background: This study aimed to investigate the effects of upper-extremity heat stress combined with resistance training and resistance training alone on body composition, skill and basal fitness, isokinetic muscle strength, and anabolic hormone levels in wheelchair rugby athletes with spinal cord injury.

Methods: Fourteen male national wheelchair rugby athletes with cervical-level spinal cord injury were randomly assigned to the heat stress combined with resistance training (n=7) or resistance training group (n=7). Both groups completed a 10-week upper-extremity resistance training program. Additionally, heat stress was applied to the upper-extremity of the heat stress combined with resistance training group using steam-generating thermal sheets three times per week. Measurements conducted pre- and post-intervention included body composition, skill and basal fitness (one-hand throw, chest throw, 28 m shuttle sprint, and 20 m sprint), isokinetic strength (using the Cybex system at 60°/sec and 180°/sec), and anabolic hormones (growth hormone and insulin-like growth factor). Non-parametric tests (Wilcoxon signed-rank and Mann-Whitney U test) were used for statistical analysis (α=0.05).

Results: The heat stress combined with resistance training group showed significant increases in skeletal muscle mass and upper-extremity isokinetic elbow joint strength, particularly in flexion (%BW) and extension (%BW) at 60°/sec. Growth hormone levels increased significantly only in this group, while insulin-like growth factor levels showed marginal improvement. Both groups improved in 28 m shuttle sprint and one-hand throw; however, the heat stress combined group showed a greater effect size in the 20 m sprint. No significant changes were observed in body mass index or body fat percentage.

Conclusions: The combination of heat stress and resistance training may provide additional benefits in enhancing upper-extremity muscle strength and stimulating anabolic hormone responses in wheelchair rugby athletes with spinal cord injury. These findings suggest a promising and practical strategy for optimizing training adaptations in this athletic population.

Keywords: Spinal cord injuries, Quad rugby, Heat-shock response, Resistance training, Anabolic agents

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INTRODUCTION

Spinal cord injury (SCI) refers to the partial or complete impairment of the spinal cord resulting from trauma or disease. Such injuries induce a wide range of degenerative changes below the level of the lesion, particularly affecting musculoskeletal and metabolic functions [1,2]. Muscle atrophy following SCI is characterized by a marked reduction in slow-twitch muscle fibers and a phenotypic shift toward fast-twitch fiber predominance, which leads to decreased oxidative capacity and accelerated fatigue [3,4]. Concurrently, the lack of mechanical loading promotes bone resorption and results in a rapid decline in bone mineral density [5]. These physiological alterations, along with ectopic fat accumulation in atrophied muscles, contribute to reduced insulin sensitivity and increase the risk of type 2 diabetes and cardiovascular complications [6]. This in turn negatively affects independence in daily activities and overall quality of life [7,8].

Rehabilitation exercises have been emphasized as an intervention strategy to compensate for these functional impairments. Numerous studies have demonstrated that resistance training (RT) effectively maintains or increases muscle mass, improves body composition, and restores muscle function [9,10]. However, in individuals with SCI, the application of training programs requires careful consideration because the upper-extremity serves as the primary means of mobility and performance of activities of daily living. The upper-extremity serves as the primary means of wheelchair propulsion and weight-bearing activities, and more than 70% of individuals with SCI experience upper-extremity pain [11,12].

These characteristics are particularly evident in wheelchair sports. Wheelchair rugby is a high-intensity sport that requires substantial upper-extremity strength, muscular endurance, and technical proficiency due to the physical demands of the game [13]. Athletes engage in repetitive rotations, directional changes, acceleration, and sprinting motions, making the enhancement of upper-extremity function a crucial factor not only for sports performance but also for independent activities [14]. However, repetitive wheelchair propulsion and intense physical contact during competition expose the upper-extremity muscles and shoulder joint to continuous mechanical loading, which may increase the risk of chronic overuse injuries [15]. Consequently, high-intensity RT alone may place excessive stress on the shoulder joint, potentially increasing the risk of musculoskeletal injury. Considering these limitations, adjunctive intervention strategies are needed to alleviate muscle fatigue and tissue load while maintaining the benefits of RT. Recent studies have focused on the combination of rehabilitation exercise with adjunctive methods, such as heat stress, with a view to enhancing therapeutic effectiveness [16,17].

Heat stress induces various physiological responses, including increased local tissue temperature and blood flow, stimulation of protein synthesis, removal of metabolic waste products, reduction of inflammation, and stimulation of growth hormone (GH) and insulin-like growth factor-1 (IGF-1) secretion [18,19]. Animal and cellular studies show that repeated heat exposure promotes muscle hypertrophy and strength by enhancing protein synthesis, reducing atrophy, and activating satellite cells. Heat-induced proteins such as HSP72 facilitate protein repair and cellular protection, while increased blood flow through vasodilation improves metabolic waste removal and oxygen and nutrient delivery, supporting recovery and microvascular function [20]. Heat stress improves muscle oxygen delivery and reduces muscle fatigue before and after exercise, showing potential as a means of enhancing exercise effectiveness in athletes performing high-intensity exercises or in patients with functional limitations [21].

In particular, the application of heat stress before and after RT may promote peripheral vasodilation and improve soft-tissue flexibility, thereby reducing injury risk, enhancing training safety, and potentially augmenting the physiological benefits of RT [22]. However, research analyzing the effects of combined heat stress and RT interventions on body composition, skill and basal fitness, muscular function, and endocrine responses in individuals with SCI disabilities, particularly wheelchair athletes, is limited. Therefore, this study aimed to analyze changes in body composition, skill and basal fitness, isokinetic strength, and anabolic hormones induced by a 10-week intervention combining heat stress and RT (heat with resistance training, HRT) in the upper-extremity of wheelchair rugby athletes with SCI compared to RT alone.

METHODS

Participants

Twenty male national wheelchair rugby athletes from the Korea Wheelchair Rugby Association provided informed consent and were recruited. After excluding individuals with cardiovascular conditions or medication risks, 14 were finally selected to participate in the study. A priori power analysis indicated a

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required sample size of 20 participants (effect size [ES] f=0.35, α=0.05, power=0.80; G*Power 3.1.9.7), but attrition reduced the final sample to 14. Participants had cervical spinal cord injuries (C4–C7) or spinal muscular atrophy and were randomly assigned to the HRT or RT groups based on wheelchair rugby classification. Analysis of pre-training body composition for both the HRT and RT groups is presented in Table 1. No significant differences were observed between the groups in terms of age, height, weight, body fat percentage (BF%), skeletal muscle mass (SMM), body mass index (BMI), or SCI onset.

Study design

Experimental procedure

All participants were informed of the study purpose and procedures and were randomly assigned to the HRT or RT groups.

Table 1. Baseline characteristics of participants

Variable	HRT (n=7)	RT (n=7)	*P*-value
Age (yr)	37.1±10.4	38.4±5.9	0.783
Height (cm)	172.7±7.4	175.5±7.7	0.493
Body weight (kg)	68.4±11.2	70.0±16.3	0.834
Body fat (%)	26.0±7.3	26.4±8.0	0.940
Skeletal muscle mass (kg)	27.4±5.3	27.6±4.5	0.951
BMI (kg/m^2)	23.0±3.2	22.8±3.3	0.929
Onset SCI (yr)	5.0±2.3	6.5±2.2	0.385
Class (point)	1.79±0.86	1.79±0.86	>0.99
Career (yr)	5.29±2.36	6.43±2.76	0.421

Values are presented as mean±standard deviation.
BMI, body mass index; Career, wheelchair rugby career duration (years); Class, sports classification of wheelchair rugby players; HRT, heat with resistance training; RT, resistance training; SCI, spinal cord injury.

The HRT group received combined heat application and RT, while the control group received placebo treatment with RT. Both groups completed a 10-week program, with performance tests and blood sampling conducted pre- and post-training the intervention. The study design is presented in Fig. 1. This study was approved by the Korea University Institutional Review Board (No. KUIRB-2024-0114-01) and conducted in accordance with the Declaration of Helsinki.

Resistance training

All participants engaged in a 10-week residential training program that incorporated a structured RT component using standard weight-training equipment. The one-repetition maximum for each participant was estimated using the Smith machine bench press protocol based on the indirect prediction equation proposed by Mayhew et al. [23]. The training program was divided into three progressive phases: weeks 1–3, which focused on anatomical adaptation; weeks 4–7, which emphasized maximal strength development; and weeks 8–10, which targeted power improvement. The exercise intervention consisted of a 10-minute warm-up, 45 minutes of main exercise, and a 5-minute cool-down. The detailed training parameters for each phase are presented in Table 2.

Heat application

Heat- and steam-generating sheets (Kao Corporation) were applied to the biceps and triceps of both arms to increase muscle temperature. The safety of these sheets for human use has been verified by the Kao Corporation Safety Committee [24]. In this

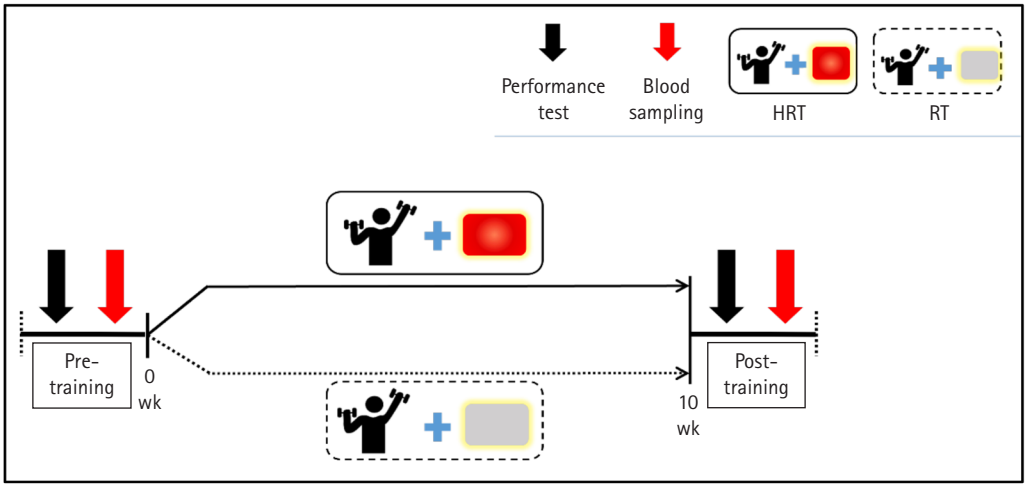

Fig. 1. Study design (exercise protocol and research design). HRT, heat with resistance training; RT, resistance training.

Table 2. Resistance training program

Type	Sebheading	Period (wk)	Intensity, 1RM (%)	Contents	Frequency
Warm-up (10 min)	Stretching & wheelchair running	1–10	Freedom	Stretching 5 min, wheelchair running 10 min	Every time
Main exercise (45 min)	Resistance training	Adaptation 1–3	60–70	Arm curl, triceps extension, lat pull down, lateral raise (front, side, behind), cable external & external rotation	3 times/wk
				8–10 Reps×3 sets	
		Maximum 4–7	90	Arm curl, triceps extension, lat pull down, lateral raise (front, side, behind), cable external & external rotation	
				3–5 Reps×3 sets	
		Power 8–10	40	Arm curl, triceps extension, lat pull down, lateral raise (front, side, behind), cable external & external rotation	
				≥15 Reps×3 sets	
Cool-down (5 min)	Stretching & wheelchair running	1–10	Freedom	Stretching 5 min, wheelchair running 5 min	Every time

Lat, latissimus dorsi; 1RM, one-repetition maximum; Reps, repetitions.

study, the heat sheets were applied exclusively to participants in the HRT group. The sheets were applied 6–8 hours before the start of the exercise session. Participants performed the exercise while wearing the heat sheets, which were removed after the completion of the exercise. The sheets were attached for 6–8 hours per day, three times per week. This application duration was determined based on previous studies reporting that thermal stimulation may influence biochemical and physiological changes in skeletal muscle [25,26]. In contrast, participants in the RT group used identical sheets with deactivated heat-generating functions. The application schedule and duration were matched with those of the HRT group to ensure experimental consistency.

Measurements and methods

Body composition

Body composition was assessed using a bedside bioelectrical impedance analyzer (InBody S10; Biospace). Participants rested supine for 10 minutes before measurement to ensure stabilization. During testing, they maintained a straight posture with arms extended approximately 15° from the torso and legs shoulder-width apart to prevent contact. Electrodes were attached to the thumbs and middle fingers and placed between the medial malleolus and heel on both sides. Participants remained still throughout the procedure. Measured variables included BF%, fat mass, SMM, and BMI for subsequent analysis.

Skill and basal fitness

We used modified version of the Beck Battery of Quad Rugby Skill Tests Test developed by Yilla and Sherrill [27] and De Groot et al. [28] was used to assess skill and basal fitness in wheelchair rugby athletes. The test included three components: (1) Explosive power and accuracy – Distance and accuracy throws using an official wheelchair rugby ball. One-hand throw and chest throw were performed three times each, and the mean value was analyzed. (2) Cardiorespiratory endurance – A 28 m shuttle sprint (out and back), with the average time of three trials recorded. (3) Anaerobic power – A 20 m sprint, with the mean time of three trials used for analysis.

Isokinetic muscle strength

The isokinetic muscle strength of the elbow joints was assessed using an isokinetic dynamometer (Cybex Humac Norm) to measure both peak torque and relative strength. Measurements were conducted with participants placed in the supine position on a Cybex examination chair. The trunk and legs were secured with straps to ensure stability. The arm was positioned close to the torso, and the shoulder was aligned with the dynamometer's axis of rotation. Elbow joint strength was then assessed in the position, with the elbow joint flexed to 90° and warmed up through 0°–100°. Bilateral elbow flexor and extensor strength were measured at 60°/sec and 180°/sec. The hand was strapped to the grip for consistency, and each muscle group was tested three times to determine peak torque.

Anabolic hormones (growth hormone and insulin-like growth factor-1)

Approximately 7 mL of resting venous blood was drawn from

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the antecubital vein by a nurse at baseline and after the 10-week intervention. Blood samples were placed in serum separation tubes and gently inverted 5–10 times to mix the clot activator and separation gel, then centrifuged (MF 300) at 3,000 rpm for 15 minutes to separate serum. The serum was stored at –80 °C until analysis. The blood samples were analyzed for the anabolic hormones GH and IGF-1 by a specialized clinical laboratory.

Statistical analysis

All data were analyzed using SPSS software (version 22.0; IBM Co.). Descriptive statistics are presented as mean and standard error of the mean. Normality tests revealed that several variables did not meet the assumption of normal distribution; therefore, non-parametric statistical methods were employed. Between-group differences were analyzed using the Mann-Whitney U test, and within-group (pre–post) comparisons were conducted using the Wilcoxon signed-rank test. All values are reported as percentage change, ES, Z-value, and *P*-value. The ES was calculated using a rank-biserial correlation, which is appropriate for nonparametric tests. The thresholds for interpreting the ESs were as follows: r=0.1 (small); r=0.3 (moderate); r=0.5 (large). The level of statistical significance was set at P=0.05.

RESULTS

Body composition

The changes in body composition indicators pre- and post-training for both groups the HRT and RT groups are presented in Table 3. No significant changes were observed in body weight, BMI, or BF% in either group. However, SMM significantly increased from pre- and post-training in both the HRT (Z=–2.366, P=0.018) and RT (Z=–2.217, P=0.027) groups.

Skill and basal fitness

The changes in skill and basal fitness indicators pre- and post-training for both the HRT and RT groups are presented in Table 4. Significant improvements were noted in the one-hand throw in the HRT (Z=–2.041, P=0.041) and RT groups (Z=–2.032, P=0.042) post intervention. However, no signifi-

Table 3. Differences in body composition across groups and time

Measurement	Category	Pre-training	Post-training	△%	ES	Z	*P*-value
BW (kg)	HRT	68.4±11.2	69.0±8.3	0.8	0.29	–1.511	0.131
	RT	70.0±16.3	71.8±15.8	2.5	0.34	–1.625	0.104
BMI (kg/m^2)	HRT	23.0±3.2	23.2±3.1	0.9	0.37	–1.687	0.092
	RT	22.8±3.3	23.2±3.9	2.0	0.27	–1.261	0.207
BF (%)	HRT	26.0±7.3	25.0±7.8	4.1	0.08	–0.085	0.932
	RT	26.4±8.0	25.7±6.9	2.4	0.08	–0.943	0.345
SMM (kg)	HRT	27.4±5.3	28.5±5.7	3.8	0.84	–2.366	0.018*
	RT	27.6±4.5	27.9±4.5	1.0	0.61	–2.217	0.027*

Values are presented as mean±standard deviation.
BF, body fat; BMI, body mass index; BW, body weight; ES, effect size; HRT, heat with resistance training; RT, resistance training; SMM, skeletal muscle mass; △%, percentage change.
*Significant difference between pre- and post-training in the group (P<0.05).

Table 4. Differences in skill and basal fitness across groups and time

Measurement	Category	Pre-training	Post-training	△%	ES	Z	*P*-value
One-hand throw (m)	HRT	3.7±1.5	5.3±1.8	29.3	0.45	–2.041	0.041*
	RT	3.4±2.0	5.4±1.2	36.8	0.54	–2.032	0.042*
Chest throw (m)	HRT	5.6±1.8	6.2±1.8	10.0	0.14	–1.000	0.317
	RT	4.8±2.2	5.6±1.8	13.7	0.07	–0.137	0.891
28 m shuttle sprint (sec)	HRT	22.6±3.5	21.5±3.1	–5.3	0.65	–2.201	0.028*
	RT	22.2±2.0	21.1±2.6	–5.4	0.59	–2.201	0.043*
20 m sprint (sec)	HRT	7.8±1.1	7.2±1.2	–7.7	0.48	–2.023	0.043*
	RT	7.7±1.2	7.4±1.2	–4.2	0.33	–1.483	0.138

Values are presented as mean±standard deviation.
ES, effect size; HRT, heat with resistance training; RT, resistance training; △%, percentage change.
*Significant difference between pre- and post-training in the group (P<0.05).

cant changes were observed in the chest throw results in either group. The 28 m shuttle sprint significantly decreased in the HRT (Z=–2.201, *P*=0.028) and RT groups (Z=–2.201, *P*=0.043) post intervention. Conversely, the 20 m sprint significantly decreased only in the HRT group post intervention (Z=–2.023, *P*=0.043), with no significant changes observed in the RT group.

Isokinetic strength changes

The changes in isokinetic elbow joint strength indicators, measured at 60°/sec pre- and post-training, for both HRT and RT groups are presented in Fig. 2A, B and Table 5. Right elbow joint flexion strength (Nm) significantly increased in the HRT group post training (Z=–1.992, *P*=0.046), however, no significant changes were observed in the RT group. No significant changes were observed in right elbow joint extension strength (Nm) in either group post-training (Fig. 2A). Relative right elbow joint flexion and extension strength relative to body weight (percentage of body weight, %BW) significantly increased post-training only in the HRT group (Z=–1.992, *P*=0.046; Z=–2.366, *P*=0.018), whereas no significant changes were observed in the RT group. The left elbow joint flexion and extension strength (Nm) and relative left elbow joint flexion and extension strength relative to body weight (%BW) showed no significant changes in either group (Fig. 2B).

The changes in isokinetic elbow joint strength indicators, measured at 180°/sec pre- and post-training, for both HRT and RT groups are presented in Fig. 2C, D and Table 6. No significant changes were observed in the right or left elbow joint flexion and extension strength (Nm) or relative flexion and extension strength relative to body weight (%BW) in either group.

Hormonal changes

The changes in anabolic hormones analysis indicators pre- and post-training for both the HRT and RT groups are presented in Table 7. GH significantly increased post-training only in the HRT group (Z=–2.366, *P*=0.018), whereas no significant change was observed in the RT group. No significant changes were observed in IGF-1 levels in either group.

DISCUSSION

The present study investigated the effects of a 10-week inter-

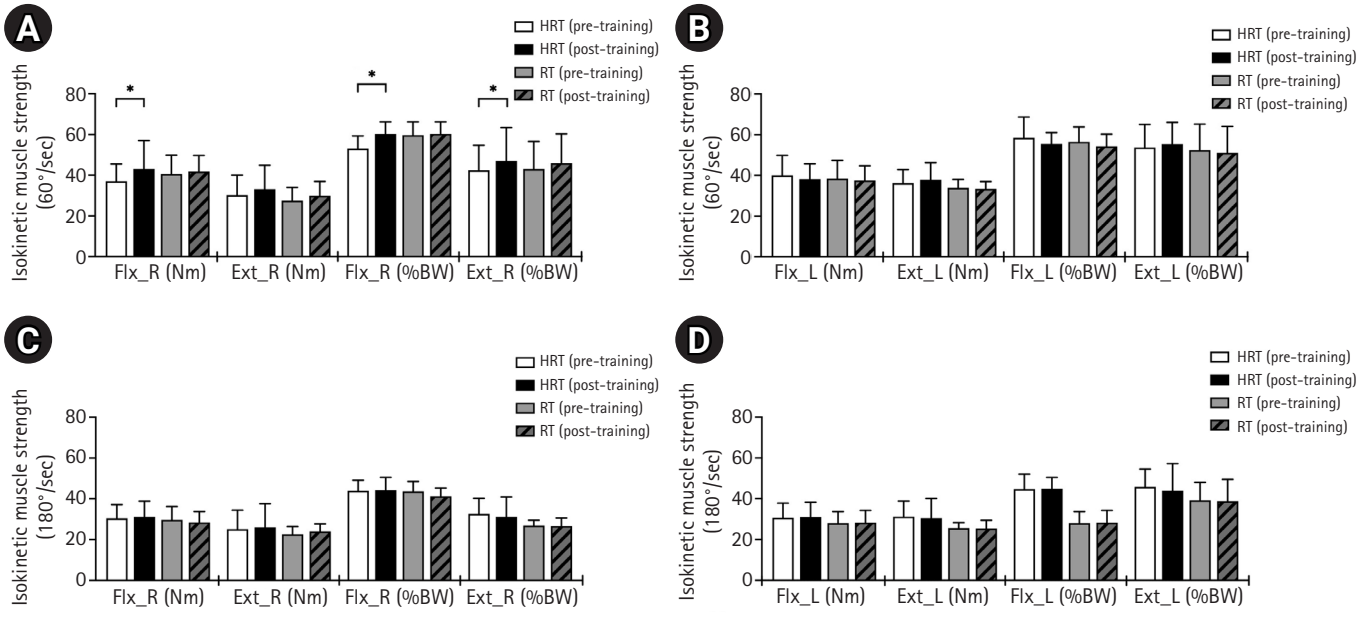

Fig. 2. Changes in isokinetic elbow joint strength pre- and post-training in HRT and RT groups. Wilcoxon signed-rank and Mann-Whitney U tests were used. (A) Right elbow joint flexion and extension strength at 60°/sec. (B) Left elbow joint flexion and extension strength at 60°/sec. (C) Right elbow joint flexion and extension strength at 180°/sec. (D) Left elbow joint flexion and extension strength at 180°/sec. Ext_L, left elbow joint extension; Ext_R, right elbow joint extension; Flx_L, left elbow joint flexion; Flx_R, right elbow joint flexion; HRT, heat with resistance training; RT, resistance training; %BW, percentage of body weight (strength relative to body weight). *Significant difference between pre- and post-training in the HRT group (*P*<0.05).

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Table 5. Differences in isokinetic elbow joint strength across groups and time (60°/sec)

Variable	Measurement	Category	Pre-training	Post-training	△%	ES	Z	*P*-value
Rt.	Flx (Nm)	HRT	37.0±8.5	43.0±14.0	14.0	0.39	−1.992	0.046*
		RT	40.6±9.2	41.8±7.9	2.9	0.15	−1.014	0.310
	Ext (Nm)	HRT	30.2±9.8	33.1±11.8	8.8	0.36	−1.363	0.173
		RT	27.5±6.5	29.9±7.0	8.1	0.55	−2.023	0.43
	Flx (%BW)	HRT	53.1±6.2	61.1±12.4	13.0	0.45	−1.992	0.046*
		RT	59.7±6.5	60.3±5.9	1.0	0.07	−0.676	0.499
	Ext (%BW)	HRT	42.4±12.3	47.1±16.3	10.0	0.47	−2.366	0.018*
		RT	43.0±13.6	45.9±14.4	6.4	0.36	−1.693	0.090
Lt.	Flx (Nm)	HRT	40.0±9.8	38.2±7.5	−4.7	0.12	−0.420	0.674
		RT	38.4±9.0	37.4±7.3	−2.6	0.04	−0.135	0.893
	Ext (Nm)	HRT	36.2±6.6	37.9±8.3	4.4	0.14	−0.631	0.528
		RT	33.9±4.1	33.3±3.6	1.8	0.04	−0.405	0.686
	Flx (%BW)	HRT	58.5±10.2	55.5±5.5	−5.6	0.15	−0.632	0.527
		RT	56.5±7.3	54.2±6.0	−4.2	0.10	−0.338	0.735
	Ext (%BW)	HRT	53.7±11.4	55.4±10.7	2.9	0.09	−0.338	0.735
		RT	52.4±12.8	51.0±13.0	−2.7	0.09	−0.507	0.612

Values are presented as mean±standard deviation.
ES, effect size; Ext, extension; Flx, flexion; HRT, heat with resistance training; Lt., left; RT, resistance training; Rt., right; %BW, percentage of body weight (strength relative to body weight); △%, percentage change.
*Significant difference between pre- and post-training in the group (P<0.05).

Table 6. Differences in isokinetic elbow joint strength across groups and time (180°/sec)

Variable	Measurement	Category	Pre-training	Post-training	△%	ES	Z	*P*-value
Rt.	Flx (Nm)	HRT	30.4±6.7	31.2±7.6	2.4	0.08	−0.674	0.500
		RT	29.7±6.5	28.4±5.3	−4.5	0.20	−1.095	0.273
	Ext (Nm)	HRT	25.1±9.3	26.0±11.6	3.5	0.09	−0.314	0.753
		RT	22.6±3.8	24.0±3.7	5.7	0.47	−2.023	0.43
	Flx (%BW)	HRT	43.9±5.2	44.3±6.2	1.0	0.01	−0.674	0.500
		RT	43.6±4.9	41.2±4.1	−6.1	0.26	−1.183	0.237
	Ext (%BW)	HRT	32.6±7.6	31.2±9.7	−4.4	0.07	−0.524	0.600
		RT	26.9±2.6	26.6±4.0	−1.2	0.01	−0.405	0.686
Lt.	Flx (Nm)	HRT	30.6±7.2	31.1±7.2	1.7	0.09	−0.841	0.400
		RT	28.0±5.6	28.3±6.0	1.0	0.01	−0.405	0.686
	Ext (Nm)	HRT	31.2±7.6	30.4±9.7	−2.8	0.03	−0.105	0.917
		RT	25.6±2.6	25.4±4.0	−0.8	0.01	−0.405	0.686
	Flx (%BW)	HRT	44.7±7.3	44.9±5.5	0.3	0.01	−0.524	0.600
		RT	28.0±5.6	28.3±6.0	−1.9	0.02	−0.845	0.398
	Ext (%BW)	HRT	45.8±8.8	43.9±13.3	−4.1	0.06	−0.105	0.917
		RT	39.2±8.8	38.8±10.7	−0.9	0.01	−0.169	0.866

Values are presented as mean±standard deviation.
ES, effect size; Ext, extension; Flx, flexion; HRT, heat with resistance training; Lt., left; RT, resistance training; Rt., right; %BW, percentage of body weight (strength relative to body weight); △%, percentage change.

Table 7. Differences in anabolic hormones across groups and time

Measurement	Category	Pre-training	Post-training	△%	ES	Z	*P*-value
GH (ng/mL)	HRT	1.30±0.65	2.02±0.85	35.8	0.68	−2.366	0.018*
	RT	1.28±0.57	1.79±0.49	28.4	0.30	−1.185	0.236
IGF-1 (ng/mL)	HRT	273.9±90.5	310.3±100.2	11.8	0.48	−1.859	0.063
	RT	271.4±92.4	299.8±98.6	9.5	0.43	−1.863	0.063

Values are presented as mean±standard deviation.
ES, effect size; GH, growth hormone; HRT, heat with resistance training; IGF-1, insulin-like growth factor 1; RT, resistance training; △%, percentage change.
*Significant difference between pre- and post-training in the HRT group (P<0.05).

vention combining upper-extremity HRT on body composition, skill and basal fitness, isokinetic muscle strength, and anabolic hormone responses in wheelchair rugby athletes with SCI. Although no significant inter-group differences were observed, the HRT intervention enhanced isokinetic strength, GH levels, and 20 m sprint performance compared with RT alone. These findings suggest that the combination of localized heat stress and resistance exercise may contribute to improvements in neuromuscular function in athletes with SCI.

In the present study, both the HRT and RT groups demonstrated significant increases in SMM, whereas body weight, BMI, and BF% remained unchanged. This pattern suggests that the intervention selectively promoted lean tissue accretion without affecting overall body mass or adiposity. The increase in muscle mass in both groups is consistent with previous findings that RT, even over relatively short intervention periods, can enhance muscle hypertrophy in individuals with SCI [29,30]. The lack of change in total body weight or body fat may be attributed to the small energy expenditure relative to total daily energy balance, or the high baseline training status of the participants, which may limit fat mass reductions [31].

The results of the present study showed that both the HRT and RT groups improved in the one-hand throw, whereas no significant changes were observed in the chest throw test. The improvement in one-hand throw performance may be related to enhanced force generation during unilateral upper-extremity movements [32].

The one-hand throw primarily relies on rapid elbow extension and flexion to accelerate the ball, and repeated propulsion RT may improve the ability to produce force during the acceleration phase of the throwing motion [33]. As a result, athletes may have been able to generate greater throwing velocity and distance. In contrast, the chest throw requires bilateral and coordinated force production with greater trunk involvement [34]. Although RT may improve upper-extremity strength, trunk muscle activation and stabilization capacity can remain limited in individuals with SCI due to impaired neural control [35]. As a result, improvements in upper-extremity strength may not necessarily translate into enhanced performance in tasks that require substantial trunk involvement. This is supported by the absence of improvement in the chest throw therefore suggests that the training adaptations were movement and limb specific, consistent with the principle of training specificity [36,37].

Regarding sprint performance, both the HRT and RT groups improved in the 28 m shuttle sprint, whereas only the HRT group improved in the 20 m sprint. The greater improvement observed in the HRT group in the 20 m sprint may reflect the additional effects of localized heat stress, which has been reported to increase blood flow, reduce muscle fatigue, and improve neuromuscular efficiency during high-intensity exercise [38,39]. In contrast, the 28 m shuttle sprint involves repeated directional changes and a slightly longer movement duration, which may rely more heavily on overall wheelchair propulsion capacity and repeated upper-extremity force production developed through RT [40,41]. Consequently, improvements in shuttle sprint performance were observed in both groups, whereas the shorter, high-intensity 20 m sprint appeared to be more responsive to the additional effects of heat stress. The present findings indicate that combining localized HRT may enhance neuromuscular adaptations in athletes with SCI.

Although no significant inter-group differences were observed, the HRT group demonstrated selective improvements in right elbow flexion peak torque and %BW, as well as right elbow extension %BW, highlighting potential enhancements in upper-extremity force production relevant to wheelchair propulsion. These selective adaptations likely reflect the functional demands of wheelchair rugby, where propulsion and ball-handling often involve asymmetric, dominant limb dependent force production [42,43]. Elbow flexors contribute during the recovery phase of propulsion, facilitating efficient arm repositioning, while elbow extensors generate propulsive force during the push phase [44]. The improvements in these specific joint actions suggest enhanced neuromuscular efficiency and motor unit recruitment in the dominant limb, supporting faster acceleration and improved sprint performance [45]. The lack of changes in other isokinetic measures may be attributed to the short duration of the intervention or the already high baseline upper-body strength of trained wheelchair rugby athletes. In highly trained individuals, adaptations are often task-specific, occurring primarily in muscles and movement patterns most frequently engaged during sport-specific activity [36]. Overall, these results suggest that HRT can selectively augment upper-extremity strength in movement patterns critical for wheelchair propulsion, potentially enhancing performance in sprint and maneuvering tasks that are central to wheelchair rugby.

In the present study, a significant increase in GH levels was observed only in the HRT group, whereas IGF-1 did not show significant changes in either group. GH is known to play an important role in protein synthesis, muscle hypertrophy, and tissue repair following exercise [46]. Previous studies have pre-

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sented that RT can stimulate GH secretion, particularly when exercise is performed at relatively high intensities or with large muscle mass involvement [47]. In the present study, the additional increase in GH observed in the HRT group may be associated with the physiological stress induced by localized heat exposure. Heat stress has been reported to stimulate endocrine responses, including increased GH secretion, possibly through thermoregulatory stress and elevated metabolic demand [48]. In contrast, IGF-1 levels did not significantly change in either group. Circulating IGF-1 responses are known to be variable and influenced by multiple systemic factors, including nutritional status, liver function, and overall metabolic regulation [49]. Another contributing factor may be that the participants were trained wheelchair rugby athletes, in whom hormonal adaptations to RT are often attenuated due to prior physiological adaptation [47]. Finally, muscle adaptation can occur through local IGF-1 expression within skeletal muscle without altering circulating concentrations, indicating that the lack of significant change in serum IGF-1 does not necessarily reflect the absence of anabolic adaptations.

To our knowledge, this is the first study to investigate combined heat stress and upper-extremity RT in wheelchair rugby athletes with SCI. Although the effects were modest and condition-dependent, the results suggest that the unique physiological characteristics of athletes with disabilities may enhance the benefits of heat stress, supporting its integration into rehabilitation training. Future research should include longer interventions, athletes from various wheelchair sports, and additional training stimuli such as heat exposure and blood flow restriction tailored to adaptive sports populations. One limitation of this study is that the final sample size was slightly smaller than the number suggested by the a priori power analysis, which may have reduced the statistical power of the study. Therefore, the findings should be interpreted as preliminary evidence, and future studies with larger sample sizes are warranted.

In conclusion, although no significant inter-group differences were observed, HRT showed potential for enhancing muscular strength and function in athletes with SCI. The combination of upper-extremity heat stress and RT improved isokinetic strength, GH levels, and 20 m sprint performance compared to RT alone, suggesting enhanced neuromuscular function. No significant changes were observed in body fat or BMI. These findings indicate that localized heat stress may be an effective adjunct to RT, warranting further research to refine protocols and examine long-term outcomes.

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AUTHOR CONTRIBUTIONS

Dr. Sung Jin YOON had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. All authors reviewed this manuscript and agreed to individual contributions.

Conceptualization: MJL and JML. Data curation: MJL and JML. Formal analysis: SJY. Methodology: MJL and JML. Writing–original draft: MJL and JML. Writing–review & editing: MJL and SJY.

CONFLICTS OF INTEREST

No existing or potential conflict of interest relevant to this article was reported.

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DATA AVAILABILITY

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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How People Decide to Protect Their Health: A Protection Motivation Theory–Theory of Reasoned Action Perspective

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ABSTRACT

Background: This study investigated how perceived knowledge, threat, and coping appraisals, moral obligation, and social approval influence voluntary mask-wearing intentions within an integrated framework combining Protection Motivation Theory (PMT) and the Theory of Reasoned Action (TRA). Understanding the drivers of protective behaviors after mandates are lifted is essential for sustaining public health practices. In the United States—where mask wearing is not culturally normative—such behaviors rely on internal motivations rather than external enforcement.

Methods: Using data from a nationwide online survey of 360 U.S. adults, structural equation modeling was employed to test relationships among perceived knowledge, threat appraisal, coping appraisal, moral obligation, social approval, and behavioral intention.

Results: Perceived knowledge significantly predicted both coping and threat appraisals. Coping appraisal influenced moral obligation, while threat appraisal affected both moral obligation and social approval. Among all predictors, only moral obligation significantly predicted behavioral intention, which in turn predicted protective behavior.

Conclusions: These findings highlight the central role of moral obligation and coping appraisal as key drivers of voluntary health protective intentions. The integrated PMT–TRA model provides actionable insights for sustaining motivation in low-threat contexts and offers guidance for shaping future public health strategies.

Keywords: Health behavior, Attitude to health, Theory of planned behavior, Moral obligations, Face mask

INTRODUCTION

Seasonal influenza activity has increased globally since October 2025, with influenza A (H3N2) predominant and co-circulation of other respiratory viruses such as respiratory syncytial virus (RSV) [1]. In the U.S., influenza infections are growing or are likely to grow in 47 states, RSV is rising in multiple regions, and COVID-19 activity is trending upward [2]. These concurrent viral trends demonstrate that respiratory infectious diseases continue to pose substantial public health risks even after the acute phase of the COVID-19 pandemic. The COVID-19 pandemic itself profoundly reshaped global health behaviors, resulting in millions of infections and deaths worldwide by late 2024 [3,4]. Before vaccines became widely available in early 2021, non-pharmaceutical interventions (NPIs), including social distancing, quarantine, and mask use, were essential for reducing viral transmission [5,6]. Public health authorities consistently promoted mask-wearing, hand hygiene, and physical distancing

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as primary preventive strategies [7-9], reflecting longstanding evidence that these behaviors mitigate respiratory infection risks in shared environments [7]. Scientific support for mask effectiveness, reinforced by clear public health messaging, contributed to widespread acceptance of mask use during the pandemic [7,10,11]. As societies transition away from mandated NPIs, understanding the psychological and social drivers of voluntary protective practices becomes increasingly important for future preparedness. Although mask-wearing initially emerged as a mandated public health measure, its continuation in voluntary contexts reflects complex psychological, social, and expressive dimensions. Studies indicate that masks do not necessarily impede social interaction [12] and can even enhance aspects of self-expression [13]. These findings suggest that mask use carries multifaceted meanings (e.g., protective, social, and symbolic), highlighting the need for theoretical perspectives that extend beyond compliance-based explanations [14-16].

To address this gap, this study integrated Protection Motivation Theory (PMT) and the Theory of Reasoned Action (TRA) [14-17]. PMT explains health-protective behavior through threat appraisal (perceived severity and vulnerability) and coping appraisal (self-efficacy, response efficacy, and perceived costs) [18-20]. TRA emphasizes the role of attitudes and subjective norms in shaping behavioral intention, including moral obligation as an internalized motivation to behave responsibly toward others [14,21]. Although extensive research has examined protective behaviors during mandatory enforcement periods, few studies have integrated PMT and TRA to investigate voluntary mask-wearing in post-mandate, low-risk settings. To address this gap, this study applies an integrated PMT–TRA framework to examine the psychological and social determinants of voluntary health-protective behavior. Therefore, this study aimed to investigate how perceived knowledge, threat appraisal, coping appraisal, social approval, and moral obligation collectively shape individuals' intentions and mask-wearing behavior within an integrated PMT–TRA framework. By identifying these determinants, the study extends theoretical understanding of voluntary health-protective behaviors in the post-mandate era and offers actionable insights for public health communication and preparedness strategies.

Protection motivation theory

PMT explains how people evaluate a health threat and their ability to cope with it when deciding whether to engage in protective behaviors [16,17]. Two interrelated processes (threat appraisal and coping appraisal) jointly shape protection motivation. Threat appraisal reflects the perceived severity, vulnerability, and the rewards of not acting; higher perceived severity and vulnerability, along with lower maladaptive rewards, support adaptive action [22,23]. Coping appraisal reflects beliefs about response efficacy, self-efficacy, and response cost; stronger efficacy beliefs and lower perceived costs promote protective behavior [20,23].

PMT has been widely applied to health and environmental actions. For example, hope and fear dynamics predicted adaptive changes during the pandemic [22], and classic experiments demonstrated how PMT components drive adaptive versus maladaptive coping [23]. Beyond infectious disease, PMT has explained sustainable behaviors such as waste management [24] and offers practical guidance for persuasive health communication [25]. Empirical COVID-19 research also links threat and coping processes to adherence behaviors (e.g., social distancing) across countries [26] and to vaccination intentions in diverse contexts [27,28]. Because appraisal processes depend on what people know, perceived knowledge is a precursor to both coping and threat appraisals, and often predicts stronger intentions to act [27,28]. Furthermore, threat and coping appraisals are central drivers of adaptive protective behavior [21,29,30]. Stronger coping appraisal (higher self-/response efficacy, lower cost) encourages adherence to guidelines and reduces maladaptive responses [31]. Based on the view that appraisals can activate social (normative) and moral (attitudinal) motives, we proposed:

H1. Perceived knowledge positively affects (a) coping appraisal and (b) threat appraisal.

H2. Coping appraisal positively affects (a) social approval and (b) moral obligation.

H3. Threat appraisal positively affects (a) social approval and (b) moral obligation.

Theory of reasoned action (adaptive responses)

The TRA posits that behavioral intention, the most immediate predictor of behavior, arises from attitude toward the act and subjective norm (perceived social pressure) [32]. In health contexts, subjective norms reflect expectations from family, friends, and peers. Observing peers who reject masking weakens compliance, whereas supportive norms reinforce it [33-35]. In this study, attitude is conceptualized as moral obligation—an internalized sense of duty to protect others. Moral obligation sustains prosocial action when external enforcement is low and has

been shown to predict collective preventive behaviors during health crises [36-38]. Finally, extensive meta-analytic evidence confirmed that behavioral intention consistently predicts actual behavior across diverse health domains [39].

H4. Social approval (subjective norm) positively influences behavioral intention.

H5. Moral obligation (attitude) has a positive effect on behavioral intention.

H6. Behavioral intention positively affects behavior.

Integrated framework for health-protective behavior

Drawing on the literature reviewed above, this study integrated PMT and TRA into a unified conceptual framework to explain voluntary health-protective behavior. PMT accounts for how individuals appraise health threats and their capacity to respond effectively, while TRA addresses the role of social norms and attitudinal factors in forming behavioral intentions. This integrated framework provides a more comprehensive account of protective behaviors, such as mask-wearing, in post-mandate contexts, where continued engagement depends on internal motivation rather than an external mandate (Fig. 1).

METHODS

Sample and sampling

A web-based survey questionnaire was employed for this study. The online survey collected a nationwide convenience sample of consumers in the United States through a crowdsourcing marketplace (e.g., MTurk). The study was approved by the Institutional Review Board (IRB) of Florida State University (IRB No. STUDY# 00002266). This study used a face mask as a stimulus to examine health-protective behavior. Using a face mask in this type of research is considered appropriate because it is a visible and widely recognized health-protective behavior during infectious disease outbreaks. It effectively represents individuals' perceptions of risk, susceptibility, and motivation to protect their health. Additionally, the use of a mask highlights how attitudes, perceived knowledge, and social norms influence health-protective practices.

The online survey took approximately 19 minutes to complete. A total of 587 surveys were initially completed by individuals in the United States who wore face masks during the COVID-19 pandemic. The final sample was reduced from 587 to 404 surveys due to the deletion of cases with incomplete questionnaires. In addition, qualification questions (e.g., frequency, types of masks) were included to filter out inattentive

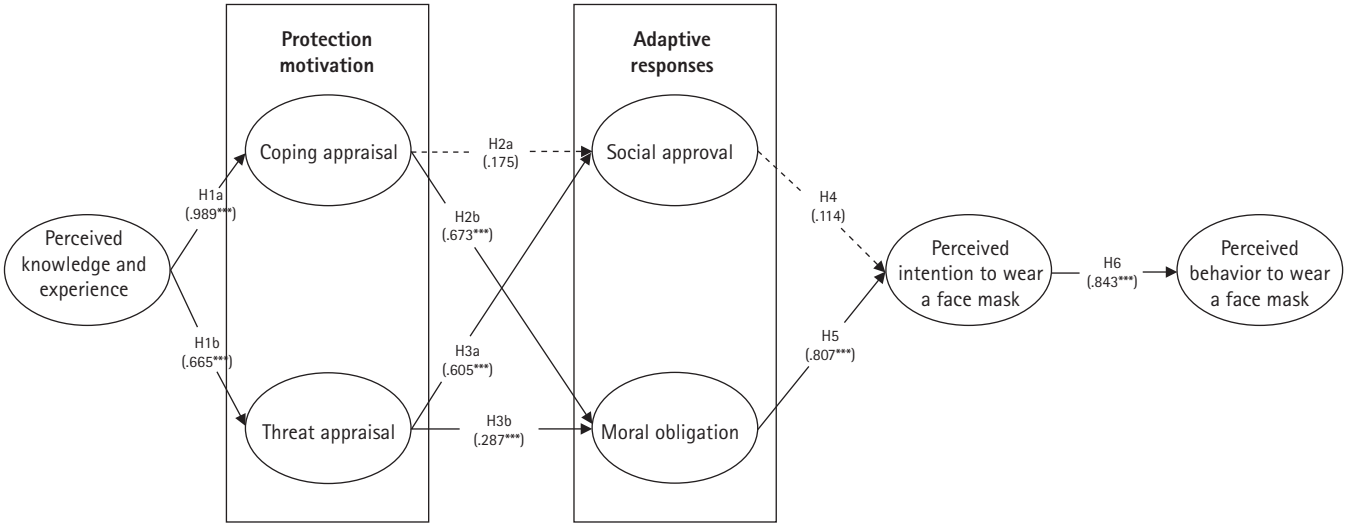

Fig. 1. Hypothesis testing for indirect and direct paths.

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and bot responses. For example, respondents were first asked to provide answers about their mask usage behavior. Then, the survey presented images of different types of masks (i.e., surgical, fashion, N95, natural fabric). Incorrect responses were removed. In addition, responses completed in a relatively short time (10 minutes) and straightliners (identical values across all items) were excluded to ensure data quality. Finally, the data were examined to detect multivariate outliers using z-score screening [40]. Raw scores were transformed into z-scores, and values that exceeded |2.58| were removed. After applying these screening procedures, 360 data were retained for further analysis.

Instrument

The survey questionnaire consisted of two sections: demographics and constructs with multiple-item measurements adapted and modified from previous research [41-44]. To test the hypothesized paths in the proposed conceptual framework, multiple-item measurements: perceived knowledge (three items), threat appraisal (three items), coping appraisal (four items), social approval (four items), moral obligation (five items), perceived intention (five items), and perceived behavior (five items), were anchored on a 7-point Likert-type scale.

Data analyses

SPSS 29 (IBM Corp.) and Mplus 9 statistical packages (Muthén & Muthén) were used to achieve this study's purpose and test hypotheses. With SPSS 29, descriptive analysis was conducted to analyze preliminary results and determine sample demographics. Using Mplus 9, confirmatory factor analysis was performed to validate the psychometric properties of the measured variables, while structural equation modeling (SEM) was employed to test the hypotheses.

RESULTS

Demographic analysis

Of the 360 respondents, male participants were 48.3% (n=174) with an average age of 43.78, while 30.0% (n=108) had annual incomes between $50,000 and $74,999. The majority of the respondents were full-time employees and had a college degree (n=216). A total of 74.7% of respondents were Caucasian, followed by Asian (13.3%) and African American (6.1%).

Preliminary analysis

Mardia's coefficients were used to construct multivariate skewness and kurtosis to test the multivariate normality assumption. Multivariate skewness (z=270.184, standard deviation [SD]=1.92, $P<0.001$) and multivariate kurtosis (z=1,442.32, SD=4.30, $P<0.001$) were found to be significant, indicating a violation of the multivariate normality assumption. To mitigate the non-normal distribution, we employed a robust estimation technique, specifically maximum likelihood mean-adjusted estimation, in our data analyses [45].

Measurement validation

The psychometric properties of the measurement model are reported in Table 1. The internal consistency of the latent variables was examined using Cronbach's alpha. All Cronbach's alpha coefficients for the variables were greater than 0.70. Additionally, composite reliability values exceeded 0.70. Factor loadings (λ) for each item within the measured latent variables were assessed to examine the strength of the relation between the latent variable and item (λ>0.50) [46]. One item in the coping appraisal was removed due to the low factor loading. The revised measurement was assessed, and factor loadings exceeded the suggested threshold of 0.50. The average variance extracted (AVE) was also assessed to understand whether the factor explains more variance than error [47]. All AVE values of the latent variables were greater than 0.50. Based on the results, the convergent validity was identified in this study.

Moreover, discriminant validity was tested using the Heterotrait-Monotrait ratio (HTMT) of the correlations [48]. According to Henseler et al. [49], an issue arises with discriminant validity when HTMT values exceed 0.85. In this study, discriminant validity was ensured because all HTMT values were lower than 0.85 (Table 2). Finally, the measurement model demonstrated an acceptable fit of the data (Satorra-Bentler scaled chi-square [S-B χ^2] =792.73, degree or freedom [df]=351, S-B χ^2/df=2.51, Comparative Fit Index [CFI]=0.933, Root Mean Square Error of Approximation [RMSEA]=0.06, Standardized Root Mean Square Residual [SRMR]=0.05).

Exploratory results

After confirming the psychometric properties of the measurement model, we proceeded with SEM to test the hypotheses in this study. The SEM demonstrated acceptable fit (S-B χ^2=1,142.43, df=449, S-B χ^2/df=2.54, CFI=0.909, RMSEA=0.06, SRMR=0.07). In terms of hypothesis testing, SEM revealed

Table 1. The measurement model

Construct & item	λ	CR	AVE
Perceived knowledge		0.74	0.50
I know exactly how the face mask will protect me from the pandemic	0.63		
I know exactly by what kind of mechanism the face mask will activate to protect my mouth and nose against the COVID-19 viruses	0.55		
The face mask plays an important role in protecting our lives	0.89		
Threat appraisal		0.83	0.62
If I get a flu-like symptom tomorrow, I will be very worried	0.79		
In the past experience, I will be worried that I might get pandemic or epidemic	0.79		
Compared to other people, I think it is likely that I will get pandemic or epidemic the in future	0.77		
Coping appraisal		0.89	0.69
Wearing a face mask is going to reduce the possibility to get COVID-19	0.78		
Wearing a face mask is important to me	0.84		
Wearing a face mask will significantly reduce the possibility of getting COVID-19	0.86		
Wearing a face mask will have a positive influence on my health status	0.82		
Social approval		0.90	0.71
Wearing a face mask helps me gain social approval	0.88		
Wearing a face mask makes a good impression on others	0.88		
Wearing a face mask affects how people perceive me	0.67		
Wearing a face mask makes me feel accepted by others	0.91		
Moral obligation		0.93	0.75
I feel obligated to wear a face mask for my health	0.86		
I feel obligated to wear a face mask for my family's health	0.88		
I feel obligated to wear a face mask for other people's health	0.90		
Everybody should be obligated to wear a face mask in public settings	0.87		
Wearing a face mask should keep me or others safe in public settings	0.81		
Perceived intention to wear a face mask		0.86	0.56
I am willing to wear a face mask in a public setting	0.76		
I am ready to wear a face mask in a public setting	0.73		
I will make an effort to wear a face mask in a public setting	0.93		
Before the pandemic, I will prepare a face mask for an emergency	0.88		
Before the pandemic, I will prepare a face mask as an emergency plan	0.73		
Perceived behavior		0.90	0.66
I have been wearing a face mask in a public setting	0.76		
I have been wearing a face mask behavior for the pandemic/epidemic	0.73		
I have been recommending my (relative) families wear a face mask	0.93		
I have been recommending my friends wear a face mask	0.88		
I have been recommending people wear a face mask on social media	0.73		

AVE, average variance extracted; CR, composite reliability; λ, standardized loading.

Table 2. Assessment of discriminant validity using HTMT

	PKW	TA	COA	SOA	MOB	WEAR	PB
PKW	-						
TA	0.53	-					
COA	0.83	0.63	-				
SOA	0.44	0.71	0.55	-			
MOB	0.63	0.71	0.84	0.65	-		
WEAR	0.62	0.67	0.77	0.55	0.79	-	
PB	0.58	0.73	0.75	0.70	0.79	0.76	-

COA, coping appraisal; HTMT, Heterotrait-Monotrait Ratio; MOB, moral obligation; PB, perceived behavior to wear a face mask; PKW, perceived knowledge; SOA, social approval; TA, threat appraisal; WEAR, perceived intention to wear a face mask.

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that perceived knowledge had a significant effect on coping appraisal (H1a: β=0.989, standard error [SE]=0.017, *P*<0.001) and threat appraisal (H1b: β=0.665, SE=0.052, *P*<0.001). Only coping appraisal had a significant effect on moral obligation (H2b: β=0.673, SE=0.064, *P*<0.001), but there was no significant effect on social approval (H2a: β=0.175, SE=0.120, *P*<0.110). Threat appraisal positively affected social approval (H3a: β=0.605, SE=0.010, *P*<0.001) and moral obligation (H3b: β=0.287, SE=0.070, *P*<0.001). Perceived intention to wear a face mask was only significantly associated with moral obligation (H5: β=0.807, SE=0.063, *P*<0.001), but not social approval (H4: β=0.114, SE=0.075, *P*=0.127). Lastly, the perceived intention to wear a face mask significantly influenced perceived behavior (H6: β=0.843, SE=0.046, *P*<0.001).

Additional post hoc analyses were conducted to investigate mediating effects. Perceived knowledge did not have significant positive effects on perceived behavior through coping appraisal, social approval, and perceived intention to wear a face mask (β=0.013, SE=0.016, *P*=0.417; 95% confidence interval [CI]=–0.016 to 0.075) and through threat appraisal, social approval, and perceived intention to wear a face mask (β=0.071, SE=0.051, *P*=0.165; 95% CI=–0.006 to 0.101). In contrast, perceived knowledge had significant positive effects on perceived behavior through coping appraisal, moral obligation, and perceived intention to wear a face mask (β=0.394, SE=0.062, *P*<0.001; 95% CI=0.274–0.514) and through threat appraisal, moral obligation, and perceived intention to wear a face mask (β=0.149, SE=0.036, *P*<0.001; 95% CI=0.135–0.459).

DISCUSSION

This study advanced understanding of the psychological mechanisms that shaped health-protective intentions during a public health crisis. Perceived knowledge emerged as a key antecedent, significantly influencing both coping and threat appraisals. Individuals with greater knowledge were more likely to perceive a health threat as both serious and manageable, consistent with past findings in risk communication and protection motivation research [17,41]. This dual appraisal strengthened perceived control and increased motivation to adopt protective behaviors.

The results further clarified the distinct roles of coping and threat appraisals in shaping moral and social determinants of behavior. Coping appraisal significantly predicted moral obligation but not social approval. This pattern suggested that when individuals felt capable of effectively responding to a health threat, they internalized protective behaviors such as mask-wearing as a personal responsibility rather than a socially driven action. In contrast, threat appraisal significantly predicted both social approval and moral obligation, indicating that heightened threat perception activated both normative expectations and moral concern. These findings aligned with prior research demonstrating that perceived threat can heighten conformity to social norms and moral expectations [50]. Moral obligation emerged as the most influential predictor of mask-wearing intention, whereas social approval did not significantly affect intention. This finding may reflect two complementary explanations. First, in voluntary, post-mandate contexts, health-protective behaviors are more likely governed by internalized values than by perceived social pressure, thereby diminishing the predictive role of normative influence. Second, the non-significance of social approval may partly reflect the relatively narrow operationalization of subjective norms in this study. By conceptualizing subjective norms as social approval, emphasizing the prosocial dimensions of masking, the measure may not have fully captured broader normative pressures such as injunctive norms or social conformity. Similarly, attitude was operationalized as moral obligation, which, while appropriate for the voluntary behavior context examined here, did not encompass the full range of attitudinal dimensions posited by TRA, such as instrumental attitudes. Behavioral intention subsequently predicted actual mask-wearing behavior, supporting established theories linking intention to action [33]. Consequently, these results underscore the importance of integrating cognitive evaluations with moral processes when examining voluntary health-protective behavior.

This study extended PMT by formally incorporating TRA constructs, specifically moral obligation and social approval, into a unified framework for explaining voluntary health-protective behavior. Few studies have integrated these two theories in this manner, particularly in post-mandate contexts where behavior is driven by internal rather than external motivation. This integration advanced theoretical understanding by linking cognitive appraisal processes with normative and attitudinal pathways, offering a more comprehensive account of adaptive responses. Furthermore, the findings demonstrated that perceived knowledge shaped behavioral intentions indirectly through both coping and threat appraisals, highlighting the importance of examining mediating mechanisms in health-protective behavior models.

The results offered several actionable insights for public

health communication. Campaigns should emphasize clear, accurate knowledge to strengthen coping efficacy and reinforce individuals' moral responsibility to protect themselves and others. Messages that frame mask-wearing as an act of safeguarding the community may activate moral obligation more effectively than compliance-based appeals. Strengthening social norms through trusted community leaders, public health ambassadors, or influential figures may also enhance message credibility and collective engagement [8,36]. Such integrated messaging strategies may promote sustained preventive behaviors across diverse public health contexts.

Although the present study was conducted within a U.S. context, the findings may carry broader implications for public health practice in other countries, including South Korea. South Korea has demonstrated consistently high rates of voluntary mask adoption during and beyond the COVID-19 pandemic, a pattern that aligns with the central role of moral obligation identified in the present study. Cultural values that emphasize responsibility toward others and community well-being may further amplify the influence of internalized moral motivation on health-protective behavior. Future research should examine whether these findings generalize across cultural contexts, and comparative studies between the United States and South Korea may offer particularly valuable insights given their contrasting cultural orientations toward individual and collective health responsibility.

Conclusion

This study integrated PMT and TRA to explain how individuals form intentions and engage in voluntary health-protective behaviors. The findings highlighted the central influence of cognitive appraisals, particularly perceived knowledge and efficacy, alongside moral obligation in shaping protective intentions and actions. By demonstrating how cognitive, social, and moral determinants interact, the study provided a theoretically grounded and empirically supported account of the psychological mechanisms that drive preventive behavior.

The conceptual model developed here extends beyond the context of COVID-19. Its emphasis on perceived control, ethical responsibility, and internalized motivation offers a transferable framework for understanding a wide range of health-protective behaviors, including vaccination, respiratory hygiene, and chronic disease prevention. Integrating cognitive appraisal with moral and social motivations clarifies how individuals translate understanding into action. These insights can inform public health communication, behavior change strategies, and emergency preparedness planning.

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AUTHOR CONTRIBUTIONS

Dr. Changhyun NAM had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. All authors reviewed this manuscript and agreed to individual contributions.

Conceptualization: CN, HYY, and JL. Data curation: CN and HYY. Formal analysis: CN and HYY. Investigation: CN. Methodology: CN and HYY. Validation: CN and HYY. Visualization: CN and HYY. Writing–original draft: all authors. Writing–review & editing: all authors.

CONFLICTS OF INTEREST

No existing or potential conflict of interest relevant to this article was reported.

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None.

DATA AVAILABILITY

The data supporting the findings of this study are not publicly available due to ethical and privacy restrictions involving human participants but are available upon reasonable request from the corresponding author.

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Erratum

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Correction to "Field Applicability of Cognitive–Motor Dual-Task Assessment in Anterior Cruciate Ligament Rehabilitation: A Systematic Review of Psychometric, Physiological, and Translational Frameworks"

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The author noted that the published article (Korean J Health Promot 2025;25(4):111-126; https://doi.org/10.15384/kjhp.2025.00164) contained wording that may be overgeneralized or imply broader representativeness than supported by the data, including certain expressions in Table 2 and related descriptions in the text.

The author apologizes for any confusion or inconvenience this may have caused and appreciates your understanding.

First of all, three changes were made in the main text, in the Results section and the Discussion section.

In the Results section, replace "(ICC≥0.8–0.96, SRM ≈ 0.9, setup<20 min)" with "(ICC≥0.8–0.96)" in the 'Overview of evidence across outcome domains' item.

Before modification

Across all decades, behavioral reaction-time indices and IMU-based kinematic outcomes provided the strongest psychometric evidence (ICC≥0.8–0.96, SRM ≈ 0.9, setup<20 min).

After modification

Across all decades, behavioral reaction-time indices and IMU-based kinematic outcomes provided the strongest psychometric evidence (ICC≥0.8–0.96).

In the Discussion section, delete "(SRM ≈ 0.95)" from the 'Responsiveness' item.

Before modification

Behavioral DTC (SRM ≈ 0.95) and IMU-derived asymmetry were the most change-sensitive measures of recovery progress, whereas physiological metrics (EEG/fNIRS) lacked quantitative responsiveness.

After modification

Behavioral DTC and IMU-derived asymmetry were the most change-sensitive measures of recovery progress, whereas physiological metrics (EEG/fNIRS) lacked quantitative responsiveness.

In the Discussion section, remove "setup<20 min" from the 'Large-scale multicenter validation: most urgent and highest impact' item.

Before modification

Feasibility: Wearables are already field-ready (setup<20 min, battery ≈ 12 hr).

After modification

Feasibility: Wearables are already field-ready (battery ≈ 12 hr).

These revisions do not affect the study's core findings or overall conclusions but are made to improve academic precision and to avoid potential misinterpretation.

In Table 2 below, revised information is indicated in bold.

Table 2. Study characteristics of included ACL-related wearable and dual-task investigations (n=37)

Study (year)	Sample/injury (n)	Cognitive task (type, brief)	Motor task (type)	Device/modality (make/model if reported)	Key outcomes (behavioral/physiological/kinematic—brief)	Psychometric notes (ICC, SRM)/feasibility (setup time, field)
Marques et al. (2022) [12]	11 studies (ACLR review)	-	Functional tasks (jump, gait, stairs)	IMUs (APDM, Xsens, Loadsol)	Bilateral asymmetry detected; wearables ≈ lab accuracy	ICC 0.80–0.96; field-portable
Morris et al. (2023) [13]	191 college athletes (45% injured)	Serial subtraction, fluency	Reactive balance (Push & Release)	IMUs (Opal v2, APDM Inc.)	Dual-task TTS predicted injury risk (HR=1.36/250 msec)	Reliability and test duration not reported
Li et al. (2024) [14]	60 (30 ACLR+30 controls)	-	Walk+hop tests	Flexible insole+IMU	ICC=0.91–0.98 vs. Vicon; LSI ≈ 88%	Portable system; battery life ≈ 12 hours
Nazary-Moghadam et al. (2019) [15]	22 ACLD males+22 healthy controls	Auditory Stroop test (RT+error rate)	Treadmill walking at 3 speeds (low, self-selected, high)	Vicon motion capture (5 cameras, 100 Hz); knee kinematics (LyE)	↑ Gait speed → ↓ knee flexion–extension LyE (ES=0.57); dual-task ↑ RT in ACLD; cognitive load effect ns (P=0.07); ACLD prioritized gait over cognitive task	Within-session reliability reported in earlier companion study; single-session treadmill test; feasible lab setup
Jiménez-Martínez et al. [16] (2025) (systematic review)	25 studies (≈ 670 healthy athletes, ACL risk context)	Dual-task/uncertainty manipulations (math subtraction, Stroop, reaction delay, visual distraction)	Jump-landing/sidestep/cutting	Motion capture+-force plate (majority studies)	↑ Knee valgus angle and vGRF under high cognitive load → elevated ACL injury risk; slower RTs reported	Review synthesis (no ICC reported); lab-based tasks; field translation recommended
Jiménez-Martínez et al. [17] (2025) (cross-sectional study)	30 ACLR+30 controls	Go/No-Go (proactive inhibitory control)	-	Computer task (SuperLab)	↑ RT, ↑ commission errors, ↓ accuracy in ACLR group (P<0.05)	Cross-sectional lab study; no ICC reported
Walker (2018) [18]	10 ACLR	Exergame (implicit)	Narrow-based gait	Physilog IMU+EEG/EMG	↓ Stride time variability (η^2=0.53)	Feasible
Majelan and Habibi (2022) [19]	24 youth volleyball	Visual 5-digit reading	Tuck jump	Kinovea video	↓ Jump perf (η^2=0.588)	Feasible
Avedesian (2024) [20]	Review of athlete studies (across levels)	Visual-motor RT, attention, WM	Jump-landing, cutting, gait	Smartboard, VR/AR, strobe eyewear, motion capture	↓ Knee flexion · ↑ knee load with low cognition; slower RT ↑ injury risk	Good test–retest; field-ready tools; VR setups less practical
Kacprzak et al. (2024) [21]	ACLR/review focus on neurosensory–motor integration	-	-	Narrative/theoretical	Hidden sensorimotor and cortical deficits after ACL injury; integration of sensory and motor networks emphasized	Conceptual; not quantitative
Akbari et al. (2023) [22]	24 college soccer players (18 female, 6 male; 20±1 yr)	Heading a stationary soccer ball during jump (dual-task)	Drop vertical jump (30 cm box → jump & land)	3D motion tracking+force plate	↓ Knee/hip/trunk flexion, ↓ COM; ↑ tibial shear, ↑ trunk lat. flexion, ↑ stiffness → ↑ ACL risk	Reliable (r=0.63–0.91); lab-feasible but setup complex
Lin et al. (2025) [23]	30 male division I athletes (CAI confirmed)	LED light reaction dual-task	Single-leg drop jump (30 cm)	Vicon (200 Hz), Kistler (1,000 Hz), Noraxon EMG (2,000 Hz)	↑ vGRF, ↑ ankle inversion & rotation, ↑ ROM; ↓ RF EMG → ↓ stability, ↑ sprain risk	**Lab-feasible but complex setup**
Yang et al. (2025) [24]	**22 males (11 healthy; 11 with ACL, 6+meniscus, 4+sciatic nerve dysfunction, 1)**	None (pure EMG-based computational task; no behavioral dual-task)	Lower-limb motions: sitting, standing, and stair tasks (SIT, STA, STAND)	Surface EMG (4 muscles: BF, RF, VM, SEM), 1,000 Hz sampling	Dual-branch DL model (DBWCT-EMGNet): 99.86% accuracy, R^2=0.98, RMSE=1.4°; TL improved patient performance from 85.5%→99.5% accuracy	<50 msec inference time; real-time feasible for rehab/exoskeleton applications
Song et al. (2023) [25]	Editorial	-	Various rehab	EMG, IMU, VR	Summary of 31 studies	-
Ness et al. (2020) [26]	**10 studies (review)**	Stroop, n-back	Balance, gait	Force plate, IMU	↑ DTC	-
Disegni et al. (2025) [27]	Pro soccer ACLR	Visual recognition+ACL-RSI	Hop, RSA, match sim	Isokinetic, GPS	"11 to Perf" score	Field-feasible

(Continued on the next page)

Table 2. Continued

Study (year)	Sample/injury (n)	Cognitive task (type, brief)	Motor task (type)	Device/modality (make/model if reported)	Key outcomes (behavioral/physiological/kinematic—brief)	Psychometric notes (ICC, SRM)/feasibility (setup time, field)
Ghai et al. (2018) [28]	Healthy participants; Exp I: 15, Exp II: 20, Controls: 15 (age ≈ 23–27 yr)	Real-time auditory feedback (pitch–angle, amp–velocity)	Knee repositioning (40°, 75°)	XSENS IMU, headphones	↓ Error with sound; transient adaptation	45 minutes; non-invasive; high compliance
Johnson et al. (2021) [29]	20 healthy	-	SLS (perturbed)	Vicon+EMG	Flexed trunk ↑ co-contraction	ICC>0.8
Davidoviča et al. (2025) [30]	32 youth football players (16 male/16 female; age 14.6±0.5 yr)	-	SLS+3 variations (front/middle/back; 60° knee flexion)	DAid smart socks, NOTCH IMUs, PLUX EMG	Strong correlations: hip adduction ↔ medial COP; knee flexion ↔ GM/GMx (ρ ≈ 0.84); COP2W ↔ GMx (ρ=–0.592); multiple moderate correlations between joint angles, COP and EMG	In-field feasible; non-invasive; session ≈ 45 minutes; high compliance
Lu et al. (2025) [31]	16 healthy older adults (68.4±4.4 yr)	Serial subtraction (counting down by threes from random number 90–100; verbal dual task)	Obstacle crossing on 10 m walkway; obstacle height=10%, 20%, 30% of leg length	8 camera motion system; 3 force plates	↓ Crossing speed (P=0.003); ↑ leading & trailing toe-obstacle clearance (P<0.001); ↑ pelvic anterior/posterior tilt, ↑ swing hip abduction & knee flexion; ↓ stance hip/knee adduction during dual-task	Normality (Shapiro–Wilk), homogeneity (Levene); two-way repeated ANOVA (task×height, α=0.05); power analysis lab setup feasible for older adults
Ptaszyk et al. (2025) [32] (scoping review)	ACL injury/ACLR	-	Pivot-shift, Lachman, hop/jump, gait, JPS	IMUs, accelerometers, force insoles, EM/inductive sensors	Accurate knee angle, load, and symmetry metrics	Easy to implement on-site, but standardization is needed
Lu et al. (2025) [33]	ACLR (n=20)+healthy (n=20)	-	Level walking gait at 3, 6, 12, 24 months post-op	3D motion capture (Vicon MX, UK)+dual force plates (AMTI, USA)	Gradual gait symmetry recovery over 24 months; all angles & GRF normalized except persistent knee extension moment (pKEM) asymmetry	High validity; repeated-measures design; lab-based; feasible for longitudinal tracking
Kuroda et al. (2021) [34]	Narrative review	-	Various rehab	Robotics, IMU, VR	Improved ROM, motivation, adherence	No ICC or SRM; qualitative feasibility only
Baldazzi et al. (2022) [35]	17 healthy male soccer players (21.5±3.2 yr)	-	SLS, CHT; 3 reps per limb (randomized order)	MIMU Gyko & foot; AMTI force plate	Angular velocity>acceleration metrics; dominant>nondominant limb; LSI within 85%–115%	Two-way mixed ICC (absolute agreement); MDC=SEM×1.96×√2; standardized 5-minute warm-up; 3 trials per task; field-feasible protocol
Aditya et al. (2025) [36]	23 studies (MCI/dementia)	Subtraction, recall	Gait	IMU, fNIRS, MRI	↓ Speed, ↑ variability, ↑ PFC HbO_2	**Removed**
Kiminski et al. (2025) [37]	31 female athletes	Catch/fake throw	Drop landing+drill	Force plates+IMU	↓ vGRF 25%, ↑ K:A ratio	ICC=0.90–0.91
Kimura et al. (2017) [38]	45 healthy adults	Visuospatial WM training	Elbow+knee torque tasks	EMG (Delsys) +torque chair	↓ FE2 errors (P<0.01), ↑ WM capacity	15 minutes×2 weeks feasible
Calisti et al. (2025) [39]	43 (21 ACL-injured, 22 healthy; 19–36 yr)	-	Six jump-landings (single/bilateral) under fatigued & non-fatigued states	10-camera Vicon, 2 force plates, OpenSim 4.3	Fatigue ↓ jump height (P=0.001) ↑ Borg CR10; dataset supports analysis of joint kinematics & ACL deficits	Normality (Shapiro–Wilk), ANOVA; 2,199 valid trials; standardized lab setup

(Continued on the next page)

Table 2. Continued

Study (year)	Sample/injury (n)	Cognitive task (type, brief)	Motor task (type)	Device/modality (make/model if reported)	Key outcomes (behavioral/physiological/kinematic—brief)	Psychometric notes (ICC, SRM)/feasibility (setup time, field)
Detherage et al. (2021) [40]	1 injured vs. 7 controls	Vision RT task	Training drills	Zephyr sensor+GPS	↑ BMI, slower RT, ↓ HR recovery; ANS dysregulation	Feasible; single case
Forelli et al. (2025) [41]	Narrative review (ACLR population; no N reported)	Dual-task, neurocognitive drills	Quadriceps activation, gait, hop, strength	EMG, TMS, H-reflex, dynamometer, motion capture	Persistent AMI (↓ cortical excitability, ↓ CAR, asymmetry<90%), improved with NMES, BFR, dual-task rehab	No ICC reported; clinically feasible phase-based rehab; supports neurocognitive RTS framework
Krishnakumar et al. (2024) [42]	71 studies (4 ACL groups)	-	Multi-tasks (walk, run, jump)	IMUs (Xsens, APDM, etc.)	ML-based models RMSE 0.02–0.04 BW; reliable across sagittal tasks	ICC variably reported; no pooled data; setup ~15–30 minutes typical
Calabrò et al. (2025) [43]	Narrative review (ACLR athletes/patients)	Dual-task (counting, reaction, decision)	Gait, balance, proprioceptive, neuromuscular training	Robotics, VR, biofeedback, wearable sensors, neuromodulation (TMS/TENS)	Neuroplasticity-based rehab ↓ reinjury risk (9%–29%), ↑ coordination & confidence	No ICC; qualitative; feasible but expert setup & cost limit
Ricupito et al. (2025) [44]	17 ACLR	Reverse number recall	Triple hop distance	iPad+iPhones	↓ THD, DTC (full sample): healthy 6.49%–6.66%, post-op 4.32%–4.80%;	Time: NR; low-cost, single-session feasible
Rikken et al. (2024) [45]	15 male basketball players (22.1±2.3 yr)	Visual-attention dual task - FitLights	90° near-full-speed sidestep cut (energy-absorption phase: IC → peak knee flexion)	Xsens MVN IMU system (on-court); FitLights stimulus	↓ Hip flexion (IC & peak), ↓ peak knee flexion, ↑ peak hip external rotation; no ankle changes	No ICC/SRM reported; a-priori G*Power; SPM used; on-court IMU=higher ecological validity
Schwartz et al. (2025) [46]	26 healthy adults	Visual-cognitive (go, inhibit, recall)	5-10-5 & T-test	Dashr timing gates+FitLight	ICC: 0.75–0.99; DTE: −13%; no bias	Laboratory-based setup; no test-duration reported
Sherman et al. (2023) [47]	20 ACLR vs. 20 controls	Go/No-Go visuomotor (virtual soccer)	Foot response	EEG (64ch LRP)+TMS	↓ LRP area, ↑ error, ↑ AMT, ↑ effort	Lab-based EEG/TMS setup; no duration or cost reported
Strong and Markström (2025) [48]	40 ACLR (8–59 months after ACL injury, the gender ratio is 1:1)	Cognitive-motor (decision, inhibition, WM)	Drop vertical jump	8-cam Vicon+FP	↓ flexion, ↑ vGRF, ↓ injured load	Lab-based biomechanical assessment; no explicit ICC or duration reported in text

This table summarizes study design elements, sensor modalities, and outcome domains across ACL injury, ACLR, or risk contexts. Each entry details cognitive and motor task types, wearable or laboratory measurement systems, and reported psychometric and feasibility information.

ACL, anterior cruciate ligament; ACLD, anterior cruciate ligament deficient; ACLR, anterior cruciate ligament reconstruction; AMI, arthrogenic muscle inhibition; AMT, active motor threshold; ANS, autonomic nervous system; AR, augmented reality; BF, biceps femoris; BFR, blood flow restriction; BMI, body mass index; BW, body weight; CAI, chronic ankle instability; CAR, central activation ratio; CHT, crossover hop test; COM, center of mass; COP, center of pressure; COP2W, two-dimensional center of pressure width; DL, deep learning; DTC, dual-task cost; DTE, dual-task effect; EEG, electroencephalography; EM, electromagnetic; EMG, electromyography; ES, effect size; Exp, experimental group; fNIRS, functional near-infrared spectroscopy; FP, force plate; GM, gluteus maximus; GMx, gluteus maximus; GPS, global positioning system; GRF, ground reaction force; HbO_2, oxyhemoglobin; HR, hazard ratio; IC, initial contact; ICC, intraclass correlation coefficient; IMU, inertial measurement unit; JPS, joint position sense; K:A, knee-to-ankle ratio; lat., lateral; LED, light emitting diode; LRP, lateralized readiness potential; LSI, limb-symmetry index; LyE, Lyapunov exponent; MCI, mild cognitive impairment; MDC, minimal detectable change; MIMU, magnetic-inertial measurement unit; ML, machine learning; MRI, magnetic resonance imaging; NMES, neuromuscular electrical stimulation; NR, not reported; ns, not significant; PFC, prefrontal cortex; pKEM, peak knee extension moment; post-op, postoperative; rehab, rehabilitation; RF, rectus femoris; RMSE, root mean square error; ROM, range of motion; RSA, repeated sprint ability; RSI, return to sport after injury scale; RT, reaction time; RTS, return-to-sport; SEM, standard error of measurement; SIT, sit task; SLS, single-leg squat; SPM, statistical parametric mapping; SRM, standardized response mean; STA, stair task; STAND, stand task; TENS, transcutaneous electrical nerve stimulation; THD, triple hop for distance; TL, transfer learning; TMS, transcranial magnetic stimulation; TTS, time-to-stability; vGRF, vertical ground reaction force; VM, vastus medialis; VR, virtual reality; WM, working memory; η^2, eta-squared effect size.

Revised elements are indicated in bold. "Removed" indicates information deleted in this erratum.

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Instructions for Authors

Korean Journal of Health Promotion
KJHP

Revised in January, 2024 (6th)
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Question: Is intermittent high-dose vitamin D supplementation effective in the prevention of falls and fractures?

Findings: In this meta-analysis of 15 randomized controlled trials, intermittent high-dose vitamin D supplementation showed no beneficial effect in the prevention of falls and fractures and even showed a harmful effect in the high-quality trials.

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Author Contributions

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The submitting author is responsible for completing this information at submission, and it is expected that all authors will have reviewed, discussed, and agreed to their individual contributions ahead of this time.

<Example>

Dr. MYUNG had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy

of the data analysis. All authors reviewed this manuscript and agreed to individual contributions.

Conceptualization: SKM.
Data curation: SWO and YJC.
Formal analysis: YJC.
Methodology: SKM, SWO, and YJC.
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Writing - original draft: YJC.
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