The effects of passive and active warm-ups on vertical jump, stretch-shortening cycle and reactive strength index performance

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Conglin Li

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Abstract

Passive warm-up, via hot-water immersion (HWI) for instance, may enhance explosive performance by increasing lower-limb temperature without imposing the metabolic demands associated with exercise. However, it remains unclear whether passive heating influences jump tasks with different concentric and stretch-shortening cycle (SSC) demands and whether its effects are comparable to those achieved following active warm-up (AWU). Hence, this thesis aimed to compare the acute effects of passive warm-up via HWI and AWU, on three different vertical jump performance tasks in physically active adults, including squat jump (SJ), countermovement jump (CMJ), and drop jump (DJ). Twenty participants (15 males and 5 females; age: 25.9 ± 4.5 years) completed the two warm-up conditions and a control condition (CON) via thermoneutral water immersion in a randomised crossover design. Passive warm-up involved 60 min of waist-level HWI at 42°C, whereas CON involved 60 min of immersion at 34°C. AWU comprised 15 min of cycling at a rating of perceived exertion of 14 (6-20 Borg scale), followed by dynamic lower-limb movements, 10 bodyweight squats, and 10 submaximal CMJs. The three vertical jump tests, SJ, CMJ, and DJ were assessed before and immediately after each condition on a force platform. The analysed outcomes were SJ and CMJ height and peak propulsive force (PPF), along with DJ height and reactive strength index (RSI). Change scores (post minus pre) were compared between conditions using analysis of variance (ANOVA) followed by Bonferroni-adjusted post hoc comparisons. Significant condition effects were observed for SJ height ($p < .001$), SJ PPF ($p = .002$), CMJ height ($p < .001$), DJ height ($p = .006$), and DJ RSI ($p < .001$). Bonferroni-adjusted comparisons showed that the positive changes observed following HWI differed significantly from the corresponding changes following AWU (SJ height, $p < .001$; SJ PPF, $p = .020$; CMJ height, $p < .001$; DJ height, $p = .017$; DJ RSI, $p = .011$) and CON (SJ height, $p < .001$; SJ PPF, $p = .002$; CMJ height, $p < .001$; DJ height, $p = .015$; DJ RSI, $p < .001$). CMJ PPF did not differ significantly among conditions ($p = .108$). These findings demonstrate that 60 min of waist-level HWI at 42°C can acutely improve concentric-dominant jump performance via SJ test and performance in jumps involving slow- and fast-SSC demands via CMJ and DJ, respectively. In addition, the passive warm-up via HWI enhanced RSI during DJ while AWU showed no difference to the CON condition. In conclusion, passive warm-up via 60 min of HWI at 42°C appears to be an effective strategy for acutely enhancing vertical jump performance across tasks characterised by concentric-dominant, slow-SSC, and fast-SSC demands.

Keywords: hot-water immersion, passive warm-up, active warm-up, vertical jump performance, stretch-shortening cycle

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Abbreviations

Table 1

List of abbreviations

A.U.	Arbitrary units
ANOVA	Analysis of variance
AWU	Active warm-up
BMI	Body mass index
CMJ	Countermovement jump
CON	Thermoneutral water-immersion control condition
DJ	Drop jump
EMD	Electromechanical delay
ES	Effect size
HREC	Human Research Ethics Committee
HRT	Half-relaxation time
HWI	Hot-water immersion
ICC	Intraclass correlation coefficient
MVIC	Maximal voluntary isometric contraction
MVC	Maximal voluntary contraction
P20/P100	Ratio of torque evoked at 20 Hz to torque evoked at 100 Hz
PPF	Peak propulsive force
RH	Relative humidity
RM	Repetition maximum (e.g., 1RM, 3RM, and 5RM)
RPE	Rating of perceived exertion
RSI	Reactive strength index
RTD	Rate of torque development
RTR	Rate of torque relaxation
SD	Standard deviation
SJ	Squat jump
SSC	Stretch-shortening cycle
Tc	Core temperature
Tm	Muscle temperature
TPT	Time to peak torque or tension
Tsk	Skin temperature
Tty	Tympanic temperature
VA	Voluntary activation
VL	Vastus lateralis
VO_2 max	Maximal oxygen uptake

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Chapter One
Introduction

Warm-up strategies are widely used to prepare the neuromuscular system for activities requiring rapid force production and high-power output (Bishop, 2003a; McGowan et al., 2015). Their ergogenic effects are largely attributed to increases in muscle temperature, which may reduce muscle viscosity, accelerate nerve conduction velocity, enhance metabolic reactions and improve contractile function (Bishop, 2003a; Racinais & Oksa, 2010). These adaptations are relevant to vertical jump performance, which depends on the rapid generation and transfer of lower-limb force (Petrigna et al., 2019).

Warm-up strategies can be divided into active and passive approaches (Bishop, 2003a; McGowan et al., 2015). Active warm-up involves voluntary muscular activity and may enhance performance through both thermal and non-thermal mechanisms, including increased muscle temperature, elevated oxygen uptake and neuromuscular activation (Bishop, 2003b). However, its effectiveness depends on appropriate intensity and recovery, as excessive loading may induce fatigue and reduce subsequent performance (Bishop, 2003b; Tomaras & MacIntosh, 2011). Passive warm-up uses external heating exposure methods, such as hot-water immersion or heated garments, to increase or maintain muscle and core temperature without the metabolic demand of exercise (Bishop, 2003a; McGowan et al., 2015). Passive increases in muscle temperature have been shown to enhance rapid force production and neuromuscular function, indicating that temperature elevation alone can modulate force-generating capacity (Rodrigues et al., 2021).

Vertical jump tests are commonly used to assess lower-limb neuromuscular performance because they provide practical measures of explosive strength, power and stretch-shortening cycle function (Bishop et al., 2022; Petrigna et al., 2019). The squat jump primarily assesses concentric force production, whereas the countermovement jump incorporates a preparatory eccentric phase and is commonly used to assess slow stretch-shortening cycle function (Bobbert et al., 1996; Linthorne, 2001; Schmidtbleicher, 1992). The drop jump places greater emphasis on rapid eccentric–concentric coupling and is therefore used to assess reactive strength and fast stretch-shortening cycle function (Bobbert et al., 1987; Schmidtbleicher, 1992).

The interpretation of vertical jump outcomes depends on reliable and valid testing procedures. Squat jump and countermovement jump tests have demonstrated acceptable reliability and factorial validity when standardized protocols are used (Markovic et al., 2004). Force-platform assessment provides additional information by deriving jump height and force-time variables from ground reaction force data (Linthorne, 2001).

Active and passive warm-up strategies may both enhance vertical jump performance because increases in muscle temperature can improve dynamic, high-velocity force production and rate of force development (Wilson et al., 2025). However, their effects may not be equivalent because active warm-up provides thermal, task-specific, and potential post-activation performance enhancement stimulus, whereas passive warm-up primarily provides a thermal stimulus (Bishop, 2003a, 2003b; Blazevich & Babault, 2019; McGowan et al., 2015). To better understand these mechanisms, this thesis first conducted a literature review examining and summarizing the shared and distinct physiological mechanisms underlying active and passive warm-up, together with the methodological differences in how these strategies have been applied to enhance neuromuscular performance.

Chapter Two
Literature Review

2.1 Warm-Up in Sport and Exercise Performance

Warm-up routines are widely employed in sport and exercise as preparatory strategies before training and competition (Bishop, 2003a). Traditionally, warm-up has been used to prepare the body for subsequent physical activity, reduce the risk of injury, and improve performance readiness (Safran et al., 1989). Warm-up is generally defined as a period of preparatory exercise performed before competition or training with the aim of enhancing subsequent physical performance (Hedrick, 1992). Although the effects of warm-up are difficult to generalize because protocols are often individualized according to sport, athlete characteristics, and task demands, review evidence indicates that appropriately designed warm-up strategies can produce measurable improvements in several performance outcomes, including sprinting, cycling time-trial performance, endurance exercise, and explosive lower-limb tasks such as jumping (Bishop, 2003b; Fradkin et al., 2010; McGowan et al., 2015).

Fradkin et al. (2010) reported that warm-up protocols incorporating aerobic activity, calisthenics, stretching combined with activity, loaded lower-limb exercise, jumping tasks, and sport-specific movements improved 79% of 92 performance comparisons across cycling, running, swimming, jumping, agility, throwing, and sport-specific tasks. These findings provide broad evidence that warm-up can enhance physical performance while the variation in protocols and outcomes indicates that warm-up should be interpreted according to the specific method used and the demands of the subsequent task. Consistent with this interpretation, McGowan et al. (2015) described warm-up strategies as active, passive, or combined approaches, with active warm-up commonly involving aerobic exercise, dynamic mobility, and task-specific activity, while passive warm-up uses external heating to increase or maintain body temperature without additional exercise-induced energy cost. Aerobic activity is commonly used as the initial component of active warm-up to increase physiological readiness before high-intensity performance (McGowan et al., 2015). Dynamic stretching appears beneficial for sprinting, jumping, and power-related outcomes (Behm & Chaouachi, 2011; Li et al., 2023). Plyometric and sprint-based warm-ups can improve sprint, jump, and agility performance in team-sport athletes (Silva et al., 2018). Passive heating may enhance explosive performance by increasing muscle temperature without imposing additional exercise-related fatigue, although the evidence is less developed than for active warm-up strategies (Bishop, 2003a).

2.2 Mechanisms of Warm-Up Approaches

2.2.1 Temperature-related mechanisms

Temperature-related mechanisms have been central to explanations of warm-up-induced performance enhancement since early experimental work showed that physical work capacity improved at higher body temperatures (Asmussen & Bøje, 1945). However, temperature responses should not be interpreted as a single physiological marker, because muscle temperature reflects local changes in the working muscle, whereas core temperature reflects whole-body thermal status and may not correspond directly with local contractile function (Saltin et al., 1968). Consistent with the relevance of local muscle temperature, Bergh and Ekblom (1979) reported that increased muscle temperature was associated with improved sprinting, vertical jumping, maximal dynamic strength, and power output, while maximal isometric strength was less temperature sensitive. Sargeant (1987) extended this evidence by showing that elevated muscle temperature increased short-term leg force and power output, with the greatest effects observed at higher contraction velocities. Therefore, increased muscle temperature appears particularly relevant to dynamic, high-velocity tasks requiring rapid force production and power output.

2.2.1.1 Reduced muscle and joint resistance

An increase in muscle temperature may enhance subsequent performance partly by reducing the viscous and passive mechanical resistance of muscles and joints (Bishop, 2003a). Joint stiffness is determined by several mechanical components, including elastic, viscous, plastic, frictional, and inertial stiffness, which collectively influence the resistance that must be overcome during movement (Wright & Johns, 1961). Wright and Johns (1961) provided early human evidence for this temperature-sensitive response, showing that hand cooling increased metacarpophalangeal joint stiffness by approximately 10 – 20%, whereas local heating reduced stiffness by approximately 20%. This finding suggests that elevated tissue temperature may reduce the mechanical resistance associated with joint movement (Wright & Johns, 1961). Consistently, Petrofsky et al. (2013) reported that heat increased anterior and posterior cruciate ligament flexibility and reduced the force required for passive knee flexion by approximately 25%, whereas cold produced the opposite response. Therefore, reduced resistance within the muscle – joint system may contribute to warm-up effects by allowing movement to be performed with less passive mechanical opposition.

2.2.1.2 Enhanced anaerobic energy metabolism

An increase in muscle temperature may enhance short-duration performance partly by accelerating anaerobic energy turnover during contraction (Bishop, 2003a). Early evidence showed that heat exposure increases muscle carbohydrate use, with Fink et al. (1975) reporting greater muscle glycogen utilization during exercise in hot compared with cold conditions. More direct evidence was provided by Edwards et al. (1972), who showed that local heating of the quadriceps increased high-energy phosphate degradation during repeated isometric contractions. Febbraio et al. (1996) further demonstrated that elevated muscle temperature per se increased muscle glycogenolysis, glycolysis, high-energy phosphate degradation, inosine monophosphate accumulation, ammonia accumulation, and lactate production during intense dynamic exercise, independent of changes in rectal temperature and plasma catecholamines. These findings suggest that elevated muscle temperature can directly increase anaerobic energy turnover instead of acting only through systemic heat stress. This mechanism has also been linked to maximal power-output exercise, with Gray et al. (2006) reporting greater skeletal muscle adenosine triphosphate turnover at elevated muscle temperatures. Similarly, Gray et al. (2008) showed greater adenosine triphosphate and phosphocreatine utilization in single muscle fibres following maximal sprint exercise at elevated muscle temperatures. Therefore, increased muscle temperature may contribute to warm-up-related improvements in short-duration explosive tasks by increasing adenosine triphosphate turnover through greater phosphocreatine utilisation and glycolytic flux.

2.2.1.3 Temperature and nerve conduction responses

An increase in muscle temperature may also enhance performance by improving nervous system function and increasing the transmission speed of neural impulses (Karvonen, 1992). Faster nerve-conduction velocity may support more rapid neuromuscular activation, which may be particularly relevant for movements requiring rapid force production, precise coordination, or fast responses to external stimuli (Ross et al., 2001). Therefore, increased nerve-conduction rate may contribute to warm-up-related improvements by reducing the time required for neural signals to be transmitted and converted into coordinated muscle action. However, these potential benefits depend on the magnitude and distribution of heating. An increase in local muscle temperature may enhance peripheral neuromuscular function, whereas passive hyperthermia has been shown to reduce voluntary activation and force production (Morrison et al., 2004). This impairment may partly reflect reduced motor cortical output under substantial thermal strain (Todd et al., 2005). Thomas et al. (2006) further demonstrated that marked elevations in core temperature can impair central neural drive even when local muscle temperature is controlled. Therefore, heating strategies intended to enhance performance should preferentially increase the temperature of the working muscles while limiting excessive systemic hyperthermia.

2.2.1.4 Local temperature and muscle fibre conduction velocity responses

Elevated muscle temperature has been proposed to improve explosive performance by increasing muscle fibre conduction velocity and altering the force–velocity characteristics of skeletal muscle (McGowan et al., 2015). Early experimental evidence showed that higher muscle temperature increased the rates of force development and relaxation during rapid isometric contractions (de Ruiter et al., 1999). These responses may be partly explained by faster excitation – contraction coupling, as force development and relaxation depend on calcium release from the sarcoplasmic reticulum, calcium dissociation from troponin, and calcium reuptake during relaxation (Melzer et al., 1995). This temperature-dependent effect was further supported by de Ruiter and de Haan (2000), who showed that higher muscle temperature improved the force – velocity relationship of the human adductor pollicis, indicating that warmer muscle can produce force more effectively at higher shortening velocities. Farina et al. (2005) later showed that temperature-induced changes in muscle fibre conduction properties were associated with changes in motor-unit contractile properties, supporting the link between warmer muscle, faster electrical propagation, and faster contractile responses. Gray et al. (2006) extended this mechanism to maximal power-output development, reporting that passive elevation of muscle temperature increased muscle fibre conduction velocity alongside greater maximal power output. Therefore, post-warm-up improvements in explosive tasks such as sprinting and jumping may be partly explained by temperature-related increases in muscle fibre conduction velocity, faster force development, and improved force–velocity characteristics.

2.3 Passive Warm-Up and Neuromuscular Performance

Passive warm-up is commonly defined as the use of external heating exposure methods to increase muscle and/or core temperature without relying on voluntary exercise (Bishop, 2003a). Common strategies include hot-water immersion, sauna exposure, heating packs or garments, and irradiation or diathermy (Wilson et al., 2025). These methods may increase or maintain tissue temperature while avoiding the additional metabolic cost and fatigue that can accompany exercise-based warm-up. Evidence suggests that elevated muscle temperature is more likely to enhance short-duration, rate-dependent contractile outcomes, such as rate of force development, high-velocity force production, power output, and jump performance, than maximal force production (Wilson et al., 2025). Therefore, passive warm-up may be particularly relevant for explosive neuromuscular tasks when the heating stimulus is sufficient to elevate or preserve muscle temperature before performance.

Table 2

Summary of Studies Examining the Acute Effects of Passive Warm-Up on Physical Performance

Study	Participant Characteristics	Heating Protocol	Thermal Strain Responses	Performance Outcome
Sargeant (1987)	N = 4, 3 men and 1 woman; age = 26.8 years; stature = 173.5 cm; body mass = 68.7 kg	Lower-limb HWI for 45 min at 44°C	Increased quadriceps Tm by approximately 2.7°C, reaching 39.3 ± 0.4°C.	↑ approximately 11% peak force and peak power during 20-s isokinetic cycling; ↑ mean power.
Davies et al. (1982)	N = 5 men; age ≈ 22 years	Lower-limb HWI for 30 min at 44°C	Increased Tm to approximately 39°C.	↓ approximately 20 ms TPT; ↓ HRT; ↔ maximal voluntary and evoked force.
Davies and Young (1983)	N = 5 men; age = 22.4 ± 1.1 years; stature = 182 ± 5 cm; body mass = 75.5 ± 6.4 kg	Lower-limb HWI for 30 min at 46°C	Increased Tm by 3.1°C, from 36.6 ± 0.7°C to 39.7 ± 0.4°C.	↓ 29 ms TPT, from 121 ± 18 to 92 ± 15 ms; ↓ 17 ms HRT, from 76 ± 6 to 59 ± 6 ms; ↔ MVC, CMJ height, and jump and cycling power.
de Ruiter et al. (1999)	N = 15, 7 men and 8 women; age = 21 ± 1 years	Hand and forearm HWI for 20 min at 45°C	Increased adductor pollicis Tm to approximately 37°C.	↑ twitch RTD; ↓ HRT; ↔ peak twitch torque.
Todd et al. (2005)	N = 7 healthy adults	Whole-body HWI at 40.9 ± 0.6°C until hyperthermia was achieved	Increased Tc by approximately 1.3°C, from approximately 37.2°C to 38.5°C.	↓ approximately 2.4% torque during brief elbow-flexion MVCs; ↓ approximately 12% torque during sustained MVCs; ↓ VA and HRT.
Brazaitis et al. (2011)	N = 13, 7 men and 6 women	Lower-limb HWI for 45 min at 44°C	Increased Tc to 39.4°C and Tm to 39.7°C.	↑ peak twitch torque; ↔ knee-extension MVIC.
Rodrigues et al. (2021)	N = 15 healthy adults; age = 24.9 ± 5.6 years; stature = 178.0 ± 11.4 cm; body mass = 72.8 ± 16.2 kg	Lower-limb HWI for 90 min at 42°C	Increased Tc by approximately 1.0°C and VL Tm by approximately 2.4°C.	↑ voluntary knee-extension RTD during 0–50 ms and twitch RTD; ↓ EMD and HRT.
Rodrigues et al. (2023)	N = 15 healthy adults	Lower-limb HWI for 90 min at 42°C	Increased Tc by approximately 1.0°C and VL Tm by approximately 2.4°C immediately after HWI; VL	↓ 4.2% MVIC immediately after heating; ↓ 4.3% VA immediately after heating; ↑ peak twitch torque following recovery.

Study	Participant Characteristics	Heating Protocol	Thermal Strain Responses	Performance Outcome
			Tm remained approximately 1.4°C above baseline after 15 min.	
Rodrigues et al. (2025a)	N = 20 physically active adults, 12 men and 8 women; age = 25.1 ± 2.7 years; stature = 177.1 ± 9.9 cm; body mass = 71.2 ± 8.9 kg; BMI = 22.6 ± 1.1 kg·m^{-2}	Lower-limb HWI for 45 min at 40°C or 42°C	Thermal response not assessed.	↑ CMJ height following 40°C HWI, d = 1.09, and 42°C HWI, d = 1.77, compared with control; ↑ 1.20 cm DJ height following 42°C HWI; ↔ 0.43 cm DJ height following 40°C HWI; ↑ CMJ peak force, peak power, and RSI.
Treigytė et al. (2024)	N = 12 men; age = 27.2 ± 6.6 years; stature = 186.7 ± 7.6 cm; body mass = 86.5 ± 12.1 kg; BMI = 24.9 ± 2.2 kg·m^{-2}; body fat = 16.9 ± 3.1%	Lower-limb HWI for 45 min at 44–45°C	Increased Tc to approximately 38.4°C and VL Tm to approximately 38.5–38.6°C.	↓ 2.63 ± 4.19% VA following single-phase HWI; ↓ P20/P100 ratio and HRT; ↑ RTR; ↔ maximal isometric and isokinetic torque and RTD.
Hedley et al. (2002)	N = 10 resistance-trained men; age = 23 ± 4 years	Sauna exposure for 30 min at 65–75°C and 15% RH.	Oral and tympanic temperatures increased by 2.48 and 2.71 °C, respectively	↑ 3.1% vertical-jump height; ↓ leg-press 1RM; ↓ 29.2% leg-press endurance and 15.8% bench-press endurance; ↔ bench-press 1RM.
Mornas et al. (2021)	N = 16, 9 men and 7 women; age = 24.9 ± 5.7 years; body mass = 69.8 ± 9.9 kg	Environmental heat exposure at 47.4°C	Increased Tm by approximately 3.0°C and Tc to approximately 38.4°C.	↓ twitch contraction time, HRT, and EMD; ↔ peak twitch torque.
Mornas et al. (2022)	N = 16 healthy adults	Environmental heat exposure at 47.4°C	Increased Tm by approximately 3.0°C and Tc to approximately 38.4°C.	↑ voluntary and electrically evoked RTD; ↓ VA; ↔ MVIC torque.
Périard et al. (2014)	N = 10 men	Environmental heat exposure at 48°C until the target Tc was achieved	Increased Tc to 38.5°C or 39.5°C and increased VL Tm.	↓ MVIC at a Tc of 39.5°C; ↓ VA, TPT, and HRT.
Morrison et	N = 22 men; body fat = 8.2 ± 3.9%	Whole-body heating using	Increased Tc to approximately	↓ knee-extension MVIC, VA, TPT, and HRT.

Study	Participant Characteristics	Heating Protocol	Thermal Strain Responses	Performance Outcome
al. (2004)		a water-perfused suit until hyperthermia was achieved	39.4°C.	
Thomas et al. (2006)	N = 9 healthy adults	Whole-body heating using a water-perfused suit until Tc reached 39.5°C	Increased Tc to 39.5°C and soleus Tm to 38.7°C.	↓ plantar-flexion MVIC, VA, TPT, and HRT.
Ross et al. (2012)	N = 8 healthy adults; age = 27.2 ± 6.3 years; body mass = 76.6 ± 9.1 kg	Progressive whole-body heating using a water-perfused suit supplied with 50°C water	Increased Tc by approximately 2.0°C, from 37.0 ± 0.3°C to 39.0 ± 0.4°C at the limit of thermal tolerance.	knee-extensor MVC decreased by 9 ± 10% at the limit of thermal tolerance; cortical VA decreased by 11 ± 8% at a 1.5 °C increase in Tc and by 22 ± 23% at the limit of thermal tolerance; corticospinal excitability remained unchanged.
Faulkner et al. (2013a)	N = 11 male competitive cyclists and triathletes; age = 24.7 ± 4.2 years; stature = 182 ± 7 cm; body mass = 77.9 ± 9.8 kg	Electrically heated trousers worn during a 30-min transition following a 15-min cycling warm-up	Increased pre-sprint VL Tm relative to control by approximately 1.0°C at 1-cm depth and 0.4°C at 3-cm depth.	↑ 9.6% absolute peak cycling power; ↑ 9.1% relative peak cycling power.
Faulkner et al. (2013b)	N = 11 male competitive cyclists	Electrically heated trousers worn during the active warm-up and 30-min transition, or during the transition only	Increased pre-sprint Tm by approximately 0.3°C with transition-only heating and by approximately 0.4°C with heating during both phases, compared with active warm-up alone.	↔ sprint performance between heating during both phases and transition-only heating.
Cook et al. (2013)	N = 6 Olympic-level bob-skeleton athletes, 3 men and 3 women	Blizzard survival jacket worn during the transition following warm-up	Increased Tty by 1.0 ± 0.3°C.	↑ 20-m sled-pull sprint performance, ES = 1.8.
Brown et al. (2013)	N = 20 professional male rugby league players	Blizzard survival jacket worn during a 15-min transition following an	Decreased Tc by 0.19 ± 0.08°C during the transition, compared with a decrease of 0.55 ± 0.10°C under	↓ approximately 0.05 s repeated-sprint time, from 7.01 ± 0.16 to 6.96 ± 0.14 s; ↑ lower-body peak power.

Study	Participant Characteristics	Heating Protocol	Thermal Strain Responses	Performance Outcome
		active warm-up	control, attenuating the decline by approximately 0.36°C.	
Wilkins and Havenith (2017)	N = 12 elite swimmers, 8 men and 4 women	Electrically heated jacket worn during a 30-min transition following a swimming warm-up	Increased upper-body Tsk by 2.3°C and estimated Tm by approximately 2.4°C relative to control	↓ 1.01% 50-m freestyle time in men; ↔ 50-m freestyle time in women despite a numerical reduction of 0.38%; ↑ 16.5% starting strength, 18.1% peak force, and 16.2% peak concentric power in men.
Denny et al. (2025)	N = 20 active young adults, 10 men and 10 women; age = 23 ± 2 years; stature = 172 ± 8 cm; body mass = 68.5 ± 7.2 kg; BMI = 23.1 ± 3.3 $kg \cdot m^{-2}$; body fat = 17 ± 4%	Local thigh heating using a water-perfused garment for 90 min at 50°C	VL Tm increased from 32.2 ± 1.1 °C at baseline to 36.8 ± 0.7 °C after 30 min and continued to rise by approximately 0.4 °C during each subsequent 30-min period.	↑ 8% (+10 N·m) moderate-velocity peak torque; ↑ 10% (+10 N·m) high-velocity peak torque; ↑ 14% (+155 $N \cdot m \cdot s^{-1}$) slow-velocity RTD and 15% (+20 N·m) early force production; ↔ isotonic performance.

Note. ↑ = statistically significant increase; ↓ = statistically significant decrease; ↔ = no statistically significant change. A numerical value accompanying ↔ indicates a descriptive change that was not statistically significant. For time-based performance outcomes, ↓ indicates improved performance. N = sample size; BMI = body mass index; HWI = hot-water immersion; RH = relative humidity; Tc = core temperature; Tm = muscle temperature; Tty = tympanic temperature; Tsk = skin temperature; VL = vastus lateralis; MVC = maximal voluntary contraction; MVIC = maximal voluntary isometric contraction; VA = voluntary activation; RTD = rate of torque development; RTR = rate of torque relaxation; TPT = time to peak torque or tension; HRT = half-relaxation time; EMD = electromechanical delay; CMJ = countermovement jump; DJ = drop jump; RSI = reactive strength index; P20/P100 = torque evoked at 20 Hz relative to torque evoked at 100 Hz; 1RM = one-repetition maximum; d = Cohen’s d; ES = effect size.

Table 2 summarizes studies using passive-heating and passive heat-maintenance strategies, including HWI, sauna and environmental heat exposure, water-perfused garments, electrically heated clothing, and survival jackets. The thermal and performance responses varied according to the heating intensity, duration, modality, and anatomical region exposed. Moreover, the external heating stimulus did not necessarily reflect the internal physiological dose, as comparable protocols could produce different changes in muscle and core temperature. Passive-heating protocols should therefore be interpreted according to their frequency, intensity, time, and type, together with the thermal strain achieved (Rodrigues et al., 2025a).

Studies that produced substantial increases in working-muscle temperature without excessive systemic hyperthermia have reported improvements in several measures of neuromuscular performance. Lower-limb HWI at 42–44°C increased muscle temperature by approximately 2.4–3.1°C and improved early voluntary and electrically evoked rate of force development, twitch-contractile properties, cycling force and power, and vertical-jump performance (Sargeant, 1987; Rodrigues et al., 2021, 2025b). Similarly, local thigh heating increased vastus lateralis temperature by approximately 5°C and improved torque during moderate- and high-velocity isokinetic contractions, although isotonic performance remained unchanged (Denny et al., 2025). Collectively, these findings indicate that local passive heating can improve contractile and explosive performance, although these benefits are not consistently observed across all neuromuscular tasks.

Heated garments improved power and sprint performance when used to attenuate the decline in muscle temperature during the transition following an active warm-up (Faulkner et al., 2013a; Brown et al., 2013; Wilkins & Havenith, 2017). However, these strategies primarily maintained an existing increase in temperature rather than independently producing a complete warm-up response. Sauna exposure, environmental heating, and whole-body heating produced more variable outcomes. When core temperature approached approximately 39.0–39.5°C, maximal voluntary force and voluntary activation were often reduced despite faster electrically evoked contraction and relaxation responses (Morrison et al., 2004; Thomas et al., 2006; Périard et al., 2014; Ross et al., 2012). Accordingly, the ergogenic effects of passive heating appear to depend on the heating modality, thermal dose, and performance outcome assessed. Heated garments may be most suitable for maintaining temperature following an active warm-up, whereas lower-limb HWI and local heating may be more appropriate when the primary objective is to increase working-muscle temperature. By contrast, protocols that induce substantial whole-body hyperthermia may be less suitable immediately before performance because peripheral contractile benefits may be offset by reductions in voluntary activation and central motor drive.

For the present study, waist-level HWI at 42°C for 60 min was selected to directly heat the lower-limb musculature involved in vertical jumping without inducing exercise-related fatigue. The use of 42°C was supported by evidence that both 40°C and 42°C HWI improved countermovement-jump performance, whereas an improvement in drop-jump height was observed only following the 42°C condition (Rodrigues et al., 2025b). A 60-min exposure was selected as an intermediate duration between the 45-min protocol shown to improve vertical-jump performance (Rodrigues et al., 2025b) and the 90-min protocol shown to substantially increase vastus lateralis muscle temperature and enhance early rapid force production (Rodrigues et al., 2021). Waist-level immersion was intended to prioritize lower-limb heating while limiting the systemic thermal strain associated with greater whole-body exposure. As the performance improvements following 45 min of HWI were no longer evident after a 15-min recovery period, the short transition between immersion and jump testing was used to minimize post-heating cooling and preserve the acute thermal effect (Rodrigues et al., 2025b). Thus, the selected protocol represented an evidence-informed balance between achieving sufficient lower-limb heating and avoiding excessive systemic thermal strain.

2.4 Active Warm-Up and Neuromuscular Performance

Active warm-up is commonly defined as a warm-up strategy that uses voluntary exercise to increase muscle and/or core temperature (Bishop, 2003b). Active warm-up protocols commonly include low- to moderate-intensity aerobic activity, dynamic mobility exercises, and short explosive or task-specific movements designed to progressively prepare the neuromuscular system for subsequent performance (McGowan et al., 2015). In addition to increasing temperature, active warm-up may enhance performance through increased heart rate, faster oxygen delivery, improved movement coordination, and greater neuromuscular activation (Bishop, 2003b; McGowan et al., 2015). Therefore, active warm-up should be interpreted as a flexible preparation with its effects likely influenced by the mode, intensity, duration, and timing of the warm-up in relation to the subsequent performance task.

Although active warm-up is widely used before neuromuscular performance tasks, review evidence indicates that its effectiveness is highly dependent on how the protocol is structured, including the type of activity, exercise intensity, total volume, recovery interval, and the specific performance task assessed (Fradkin et al., 2010). In particular, systematic reviews have suggested that shorter, progressive warm-up routines that include dynamic and task-specific activities are generally more favourable for explosive performance than prolonged or poorly structured protocols (Silva et al., 2018). However, methodological differences between studies make it difficult to determine whether inconsistent findings are due to the warm-up strategy itself, the magnitude of the physiological response, fatigue, or the neuromuscular test used. Therefore, Table 2 summarizes selected original studies that have examined the effects of different active warm-up protocols on explosive neuromuscular performance, including the sample characteristics, warm-up protocol, performance tests, and main findings.

Table 3

Summary of Studies Examining the Acute Effects of Active Warm-Up on Explosive Performance

Study	Participant Characteristics	Warm-up Protocol	Physical performance Outcomes	Main Finding
Tsurubami et al. (2020)	N = 9 male university athletes; age = 20.9 ± 1.0 years; stature = 1.75 ± 0.03 m; body mass = 66.4 ± 6.3 kg; BMI = 21.7 ± 2.2 kg·m⁻²; VO_2 max = 45.7 ± 3.1 mL·kg⁻¹·min⁻¹	Fifteen minutes of treadmill running at 60% or 80% VO_2 max, corresponding to 8.9 ± 1.0 and 12.5 ± 1.3 km·h⁻¹, respectively; no-warm-up control	CMJ height measured using a force plate immediately and 10 and 20 min after warm-up; best of two trials	CMJ height increased by approximately 10% and 12% immediately after the 60% and 80% VO_2 max warm-ups, respectively. The improvement remained approximately 3% at 10 min after 60% VO_2 max and approximately 8% and 4% at 10 and 20 min after 80% VO_2 max, respectively. Immediate CMJ height did not differ significantly between intensities.
Park et al. (2021)	N = 10 male sprinters; age = 16.8 ± 1.1 years; stature = 175.7 ± 4.6 cm; body mass = 67.6 ± 4.9 kg; BMI = 21.9 ± 1.0 kg·m⁻²; 100-m personal best = 11.57 ± 0.66 s	Ten minutes of jogging, dynamic stretching, and three 60-m runs, followed by eight 60-m runs at either 60–95% or 40% of self-estimated maximal speed; 1-min recovery between runs and 5-min recovery before testing	Maximal 100-m sprint time measured using a handheld stopwatch	↔ 100-m sprint time despite a numerical reduction of 0.27 s following the higher-intensity protocol, 11.83 ± 0.57 versus 12.10 ± 0.63 s.
Fletcher and Jones (2004)	N = 97 trained male rugby union players; age = 23.0 ± 8.4 years; stature = 181 ± 8 cm; body mass = 86.5 ± 14.4 kg	Ten-minute running warm-up followed by passive static, active static, active dynamic, or static–dynamic stretching	Twenty-metre sprint time measured using electronic timing; mean of two trials	Active dynamic stretching ↓ sprint time by 0.06 s, from 3.24 ± 0.20 to 3.18 ± 0.18 s. Passive and active static stretching ↑ sprint time by 0.04 and 0.05 s, respectively.
Little and Williams	N = 18 professional male soccer players	Standardised soccer warm-up followed by static stretching, dynamic	CMJ height measured using a jump mat;	↔ CMJ height. Static and dynamic stretching ↓ flying 20-m sprint time by 0.04 s versus no

Study	Participant Characteristics	Warm-up Protocol	Physical performance Outcomes	Main Finding
(2006)		stretching, or no stretching	stationary 10-m sprint, flying 20-m sprint, and agility time measured using electronic timing gates	stretching. Dynamic stretching ↓ agility time by 0.06 s versus no stretching and by 0.08 s versus static stretching.
McMillian et al. (2006)	N = 30 military cadets, including 16 men and 14 women; age = 18–24 years	Ten-minute dynamic warm-up, static-stretching warm-up, or no warm-up; 1–2 min of recovery before testing	T-shuttle time, underhand 4.1-kg medicine-ball throw distance, and five-step jump distance	Compared with no warm-up, dynamic warm-up ↓ T-shuttle time by 0.21 s and ↑ medicine-ball throw and five-step jump distances by 0.32 and 0.55 m, respectively. Dynamic warm-up was also superior to static stretching for all outcomes.
Faigenbaum et al. (2006)	N = 18 female high-school athletes; age = 15.3 ± 1.2 years; stature = 166.3 ± 9.1 cm; body mass = 61.6 ± 10.4 kg	Five minutes of jogging at RPE 9 followed by 10 min of static stretching, unweighted dynamic exercise, or dynamic exercise with a vest loaded to 2% or 6% of body mass; 2-min recovery	Vertical jump, standing long jump, seated medicine-ball throw, and 10-yard sprint	Compared with static stretching, unweighted dynamic exercise ↑ vertical-jump performance by 10.1%, while dynamic exercise with 2% body-mass loading ↑ vertical- and long-jump performance by 13.5% and 12.5%, respectively. ↔ Throw and sprint performance.
Hough et al. (2009)	N = 11 healthy men; age = 21 ± 2 years	Seven-minute static-stretching, dynamic-stretching, or no-stretching condition in a randomised crossover design	Vertical-jump height	Static stretching ↓ jump height by 4.19 ± 4.47% versus no stretching. Dynamic stretching ↑ jump height by 9.44 ± 4.25% versus static stretching.
Zois et al. (2011)	N = 10 male soccer players competing in Italian Serie D; age = 23.3 ± 2.5 years; stature = 1.78 ± 0.04 m; body mass = 69.1 ± 4.1 kg	Five-minute jog followed by a traditional team-sport warm-up lasting approximately 23 min, a small-sided game comprising three 2-min bouts, or a 5RM leg-press conditioning activity	CMJ height, reactive-agility performance, and mean 20-m sprint time during intermittent exercise	CMJ height improved by 6% after the small-sided game and 2% after the leg press. Reactive agility improved by 4% and 5%, respectively. Mean 20-m sprint time after the leg press was 9% better than after the small-sided game and 7% better

Study	Participant Characteristics	Warm-up Protocol	Physical performance Outcomes	Main Finding
				than after the traditional warm-up.
Young et al. (1998)	N = 10 resistance-trained men; age = 18–31 years; half-squat 5RM = 152.2 ± 30.1 kg	Five half-squats at 5RM followed by 4-min recovery	Loaded CMJ height measured in a Smith machine while holding a 19-kg bar; mean of five trials	↑ 2.8% loaded CMJ height, from 39.0 ± 3.3 to 40.0 ± 3.5 cm.
Gourgoulis et al. (2003)	N = 20 physically active men; age = 21.8 ± 1.1 years; stature = 1.78 ± 0.05 m; body mass = 78.4 ± 9.3 kg	Five sets of two explosive half-squats at 20%, 40%, 60%, 80%, and 90% 1RM	CMJ height measured using a force platform immediately after the protocol; best of two trials	↑ 2.39% CMJ height overall. Participants with a half-squat 1RM above 160 kg improved by 4.01%, compared with 0.42% in weaker participants; the difference between strength groups was not significant.
Chatzopoulos et al. (2007)	N = 15 male amateur team-sport athletes; age = 22 ± 2 years; stature = 186 ± 6 cm; body mass = 88 ± 3 kg; back-squat 1RM = 151 ± 12 kg	Ten single back half-squat repetitions at 90% 1RM using a Smith machine	Electronic 10- and 30-m sprint times measured 3 and 5 min after conditioning	↔ Sprint performance after 3 min. After 5 min, 10- and 30-m sprint times ↓ by 0.05 s (2.6%) and 0.08 s (1.8%), respectively.
Kilduff et al. (2007)	N = 23 professional male rugby players, including 13 senior internationals; age = 24.0 ± 3.4 years; stature = 185 ± 8 cm; body mass = 97.4 ± 13.4 kg; resistance-training experience = 3.1 ± 1.6 years	One 3RM back-squat conditioning activity performed 10 min after the baseline CMJ	CMJ peak power measured approximately 15 s and 4, 8, 12, 16, and 20 min after conditioning	CMJ peak power ↓ from 4568 ± 509 to 4430 ± 495 W approximately 15 s after the squat. Peak power ↑ by 8.0 ± 8.0% after 12 min, indicating that 8–12 min of recovery was required.
Yetter and Moir (2008)	N = 10 strength-trained men	Five minutes of cycling followed by back squats, front squats, or	Three maximal 40-m sprints measured using	Back squats ↑ running speed by 0.12 $m \cdot s^{-1}$ over

Study	Participant Characteristics	Warm-up Protocol	Physical performance Outcomes	Main Finding
		cycling-only control. Squats comprised five repetitions at 30%, four at 50%, and three at 70% 1RM; 4-min recovery before sprinting	electronic timing; average speed calculated for each 10-m section	10–20 m and by 0.18 $m \cdot s^{-1}$ over 30–40 m versus control. ↔ Speed over 0–10 and 20–30 m.
Till and Cooke (2009)	N = 12 male professional academy soccer players; age = 18.3 ± 0.7 years; stature = 176.7 ± 5.0 cm; body mass = 72.1 ± 8.0 kg; resistance-training experience = 25.7 ± 6.9 months	Jogging and dynamic exercise followed by five deadlift repetitions at 5RM, five maximal tuck jumps, three 3-s maximal isometric knee extensions per leg, or control; 4-min recovery	Electronic 10- and 20-m sprint times and CMJ height measured using a jump mat	↔ Group-level sprint and CMJ performance across conditions. Individual responses ranged from approximately −7.1% to +8.2%.

Note. ↑ indicates a statistically significant increase, ↓ indicates a statistically significant decrease, and ↔ indicates no statistically significant change. For timed performance outcomes, a decrease represents improved performance, whereas an increase represents impaired performance. N = sample size; BMI = body mass index; VO_2 max = maximal oxygen uptake; CMJ = countermovement jump; RPE = rating of perceived exertion; RM = repetition maximum

Overall, the evidence in Table 3 suggests that the most effective active warm-up for explosive performance is a progressive, multicomponent protocol instead of a single exercise modality. A general aerobic phase should first increase physiological readiness, followed by dynamic movements and task-specific explosive actions. Fifteen minutes of running at 60–80% VO_2 max improved CMJ performance, although the higher intensity maintained the benefit for longer (Tsurubami et al., 2020). However, more demanding running protocols did not consistently improve sprint performance, indicating that excessive intensity or volume may induce fatigue (Park et al., 2021). Therefore, approximately 5–15 min of moderate-to-high-intensity aerobic exercise appears appropriate, with running offering greater specificity before sprinting and cycling providing a lower-impact option before jumping or strength-based tasks.

Dynamic and task-specific exercises appear more consistently beneficial than static stretching. Dynamic warm-ups improved sprint, jump, agility, and power outcomes, whereas static stretching frequently reduced or failed to improve explosive performance (Fletcher & Jones, 2004; McMillian et al., 2006; Hough et al., 2009). The final phase should therefore include progressively intensified movements that resemble the subsequent task, such as accelerations before sprinting or squats and submaximal jumps before jump testing. Heavy resistance or loaded explosive exercises may provide additional benefits in trained individuals, but their effects are more variable and generally require approximately 4–12 min of recovery (Young et al., 1998; Kilduff et al., 2007; Till & Cooke, 2009). Collectively, a 10–20 min warm-up combining moderate-to-high-intensity aerobic exercise, dynamic movement, and task-specific actions appears to provide the most reliable preparation for explosive performance.

2.5 Vertical Jump testing in Sport and Exercise Performance

2.5.1 Importance and Applications of Vertical Jump Testing

Vertical jump performance is widely recognised as a practical indicator of lower-body neuromuscular function, as it requires rapid and coordinated force production across the hip, knee, and ankle joints to propel the body's centre of mass vertically against gravity (Linthorne, 2001). Vertical jump testing is therefore commonly used in sport and exercise science to assess key components of explosive performance, including lower-limb strength, power, rate of force development, and inter-joint coordination (Petrigna et al., 2019). Vertical jump performance has also demonstrated meaningful associations with sport-performance outcomes such as sprinting, acceleration, change-of-direction ability, and other speed–power actions, supporting its use as both a field- and laboratory-based indicator of athletic performance (Markovic, 2007).

Beyond performance profiling, vertical jump testing has been widely applied to monitor neuromuscular fatigue and training readiness, because acute or accumulated fatigue can alter jump height and force–time characteristics even when the external movement task remains unchanged (Bishop et al., 2022; Gathercole et al., 2015). However, vertical jump data should not be interpreted solely through jump height, because similar jump heights may be achieved through different force-production strategies and movement patterns (Bishop et al., 2021). Therefore, vertical jump performance should be regarded as a multidimensional neuromuscular assessment in which jump height represents the overall performance outcome, whereas force–time variables provide further insight into the mechanical strategies and physiological qualities underlying that outcome (Bishop et al., 2021; Linthorne, 2001).

Different vertical jump tests can be used to examine distinct aspects of lower-body neuromuscular performance. The squat jump (SJ) begins from a static semi-squatted position without a preceding countermovement and is therefore commonly used to assess predominantly concentric force and power production (Petrigna et al., 2019). In contrast, the countermovement jump (CMJ) incorporates a preparatory downward movement, followed by an eccentric braking phase and concentric propulsion, and is commonly used to assess explosive performance involving the slow stretch-shortening cycle (SSC) (Bobbert et al., 1996; Komi, 2000). The drop jump (DJ) begins with a drop from a predetermined height and requires the participant to rapidly absorb and reproduce force following ground contact. It therefore places greater emphasis on the fast SSC, reactive strength, and the ability to minimise ground-contact time while producing vertical displacement (Bishop et al., 2021; Bobbert et al., 1987). The reactive strength index (RSI), commonly calculated from jump height and ground-contact time, is frequently derived from the DJ to quantify this reactive ability (Bishop et al., 2021). Accordingly, the SJ, CMJ, and DJ provide related but mechanically distinct assessments, allowing concentric, slow-SSC, and fast-SSC performance to be examined separately. Understanding the mechanisms underlying these distinctions is therefore necessary before considering how different warm-up strategies may influence each jump task.

2.5.2 Vertical Jump Performance and stretch-shortening Cycle Mechanisms

The differences among vertical jump tests are largely related to whether, and how, they utilise the SSC. The SSC occurs when an active muscle–tendon unit is lengthened during an eccentric or braking phase and then immediately shortened during the subsequent concentric or propulsive phase (Komi, 2000). In vertical jumping, this sequence commonly occurs when a preparatory countermovement or landing phase precedes take-off, allowing the lower-limb muscle–tendon units to absorb force before rapidly producing upward propulsion (Nicol et al., 2006). SSC function is therefore central to understanding CMJ and DJ performance because the effectiveness of the transition from eccentric braking to concentric propulsion can influence force production, power output, and jump height (Bobbert et al., 1996).

The performance-enhancing effect of the SSC has traditionally been explained by the storage and reutilisation of elastic energy within the muscle–tendon unit (Cavagna et al., 1965). During the eccentric or braking phase, elastic structures within the muscle–tendon unit can store mechanical energy, which may then be released during the subsequent concentric phase to increase mechanical work and power output (Komi, 2000). This mechanism is dependent on the timing of the eccentric–concentric transition, because stored elastic energy may be dissipated as heat if the transition phase is prolonged (Komi, 2000). Therefore, elastic energy reutilisation provides one important explanation for why vertical jump tasks involving a countermovement or landing phase can produce greater propulsive output than an isolated concentric action (Cavagna et al., 1965).

Beyond elastic energy reutilisation, SSC performance may also be enhanced by neural and contractile mechanisms that prepare the muscle–tendon unit for effective force production before the concentric phase (Bobbert et al., 1996; Komi, 2000). Pre-activation refers to increased muscle activation before ground contact or the propulsive phase, allowing the muscle–tendon unit to develop tension and improve force transmission during the subsequent eccentric–concentric transition (Komi, 2000; Nicol et al., 2006). Active-state development provides a related explanation for why CMJ performance is typically greater than SJ performance, as the countermovement allows muscle activation and joint moments to develop before upward propulsion begins (Bobbert et al., 1996). The removal of muscle slack during the eccentric phase may further improve this process by allowing force to be transmitted more effectively at the onset of concentric propulsion (Van Hooren & Zolotarjova, 2017).

Stretch-reflex activity represents a distinct neural contribution, whereby rapid muscle lengthening stimulates muscle spindles and increases reflex-mediated motor output during the subsequent concentric action (Komi, 2000). However, the contribution of the stretch reflex depends on stretch velocity, movement duration, and the time available for reflex-mediated responses to influence force production. It may therefore be more relevant during fast-SSC actions, such as the DJ, than during slower countermovement tasks (Komi, 2000; Nicol et al., 2006).

Muscle–tendon stiffness may also influence SSC performance because it affects both elastic energy storage and the rate of force transmission during eccentric–concentric actions (Nicol et al., 2006). An appropriately stiff muscle–tendon unit can facilitate rapid force transmission and limit excessive joint displacement during fast-SSC movements, whereas excessive compliance may delay force transfer and reduce the effectiveness of the transition from braking to propulsion (Komi, 2000). However, stiffness should not be interpreted as universally beneficial, because some degree of compliance may be necessary for elastic energy storage during the eccentric phase (Nicol et al., 2006). Effective SSC performance is therefore likely to depend on an appropriate balance between stiffness and compliance, with the optimal balance varying according to the speed, loading demands, and technical characteristics of the movement (Nicol et al., 2006).

In summary, the performance-enhancing effect of the SSC should be understood as a multimechanism process involving elastic energy storage and reutilisation, pre-activation, active-state development, stretch-reflex activity, muscle-slack removal, and appropriate muscle–tendon stiffness (Bobbert et al., 1996; Komi, 2000; Nicol et al., 2006; Van Hooren & Zolotarjova, 2017). These mechanisms do not contribute equally across all jump tasks because different tests impose distinct eccentric loading demands, transition times, and requirements for force transmission (Bobbert et al., 1987, 1996). The specific SSC demands of the SJ, CMJ, and DJ must therefore be considered when interpreting their performance outcomes.

2.5.3 stretch-shortening Cycle Demands Across Vertical Jump Tests

Although the SJ, CMJ, and DJ all require rapid concentric propulsion, they differ in their movement structure and the neuromuscular qualities they are intended to assess. These distinctions are partly related to SSC speed. Slow-SSC actions are generally characterised by longer movement durations or ground-contact times, whereas fast-SSC actions involve short ground-contact times and rapid eccentric–concentric transitions (Schmidtbleicher, 1992).

The SJ begins from a static semi-squatted position and is designed to eliminate the influence of a preceding eccentric phase. It is therefore primarily used to assess concentric lower-limb force and power production with minimal contribution from SSC mechanisms (Petrigna et al., 2019). Nevertheless, successful SJ performance still requires coordinated joint extension and rapid force development during the concentric phase.

The CMJ includes a preparatory downward movement before take-off, allowing the muscle–tendon unit to undergo an eccentric braking phase followed by concentric propulsion. It is therefore commonly classified as a slow-SSC task (Bobbert et al., 1996; Komi, 2000). Compared with the SJ, the CMJ provides greater opportunity for active-state development, muscle-slack removal, and elastic energy utilisation before the propulsive phase. Its performance therefore reflects not only concentric force-production capacity but also the ability to coordinate the transition between eccentric braking and concentric propulsion.

The DJ involves stepping or dropping from a predetermined height and rapidly rebounding following ground contact. In comparison with the CMJ, it generally involves greater eccentric loading, a shorter transition period, and a stronger requirement to rapidly absorb and reproduce force (Bishop et al., 2021; Bobbert et al., 1987). The DJ is therefore commonly classified as a fast-SSC task and is used to assess reactive strength. Performance is frequently expressed using RSI, which relates the vertical displacement achieved to the time spent in contact with the ground (Bishop et al., 2021).

Accordingly, the SJ, CMJ, and DJ should be interpreted as related but mechanically distinct assessments. The SJ primarily reflects concentric force-production capacity, the CMJ reflects the ability to coordinate eccentric braking and concentric propulsion during a slow-SSC action, and the DJ reflects the ability to rapidly absorb and reproduce force under fast-SSC conditions. Examining all three tests therefore provides a broader assessment of explosive lower-body function and allows the effects of warm-up interventions to be evaluated across movements with different concentric and SSC demands.

2.5.4 Vertical Jump Performance Assessment

Vertical jump performance can be assessed using several methods, including force platforms, contact mats, optical systems, wearable sensors, and field-based jump-and-reach tests (Linthorne, 2001; Petrigna et al., 2019). Among these methods, force platforms provide the most detailed assessment because they allow jump height and force-time variables, such as peak force, impulse, power, ground-contact time, and reactive strength index, to be derived from ground reaction force data (Linthorne, 2001; Bishop et al., 2021). However, jump height alone may provide limited information about the mechanisms underlying performance changes, because the same change in jump height may result from differences in force production, movement strategy, or SSC function (Bishop et al., 2021). Vertical jump outcomes may also be influenced by several methodological factors, including starting posture, countermovement depth, arm swing, drop height, landing technique, rest interval, verbal instructions, and participant familiarization (Petrigna et al., 2019). Therefore, reliable assessment requires standardized procedures, consistent equipment, and clear reporting of the variables used to quantify performance.

In this context, the SJ, CMJ, and DJ should be selected according to the specific neuromuscular quality being investigated, and previous research has demonstrated acceptable-to-excellent validity and reliability for these assessments in young, physically active adults. Markovic et al. (2004) reported excellent reliability for SJ and CMJ height in physically active physical education students, with ICC values of .97 and .98 and coefficients of variation of 3.3% and 2.8%, respectively. Both tests also demonstrated strong factorial validity, with correlations of .81 for the SJ and .87 for the CMJ with the underlying explosive-power factor. More directly relevant to force-platform assessment, McLellan et al. (2011) found low test–retest variability for peak force, peak and mean power, and vertical jump displacement during SJ and CMJ performed by physically active young men, with coefficients of variation ranging from 2.8% to 5.1%. However, rate-of-force-development variables were less reliable, with coefficients of variation ranging from 7.9% to 11.8%. For DJ assessment, Tenelsen et al. (2019) reported moderate-to-excellent test–retest reliability for force-plate-derived ground-contact time in young, physically active adults, with ICC values ranging from .70 to .92 and coefficients of variation ranging from 3.6% to 6.4%. Agreement between the force plate and alternative measurement systems was excellent (ICC ≥ .95). Collectively, these findings support the use of force-platform-based SJ, CMJ, and DJ assessments in healthy, physically active adults, although the reliability of individual force–time variables depends on the variable selected and the degree of procedural standardization.

2.6 Summary

Overall, the studies summarised in Tables 1 and 2 indicate that appropriately designed warm-up protocols can enhance explosive performance, including vertical jumping, sprinting, and rapid force or power production, particularly when the intensity, content, and recovery period are matched to the physiological and mechanical demands of the subsequent task. These effects are commonly explained by temperature-related mechanisms, including reduced muscle and joint resistance, enhanced anaerobic energy turnover, faster nerve conduction, and improved muscle fibre conduction velocity and contractile speed. Passive warm-up can increase muscle temperature without the metabolic cost of exercise, and evidence suggests that sufficient passive heating may improve rapid force production, power output, and vertical jump performance. Active warm-up may also improve explosive performance through both thermal and non-thermal mechanisms, including movement-specific preparation and post-activation performance enhancement; however, its effectiveness appears highly dependent on intensity, duration, recovery, and individual tolerance. Vertical jump tests provide a useful model for examining these effects because the SJ, CMJ, and DJ represent different muscle contraction and stretch-shortening cycle demands. Despite this evidence, it remains unclear whether passive heating can produce performance benefits comparable to active warm-up across different vertical jump tasks. This gap provides the basis for the following section, which outlines the specific research problem addressed in the present study.

Chapter Three
State of Problem

According to current evidence presented in this literature review, both active and passive warm-up strategies may be effective for improving neuromuscular performance when protocols are appropriately designed with consideration of participant characteristics, warm-up intensity and duration, and the type of sport-performance assessment used. These strategies share a common physiological rationale, primarily through an increase in muscle temperature, which may enhance rate-dependent contractile function, force production, and explosive performance (Wilson et al., 2025). Mild increases in core temperature, heart rate, peripheral blood flow, oxygen delivery, and substrate availability may also contribute to improved performance. However, active warm-up produces these responses through voluntary muscular activity and may provide additional neural and movement-specific preparation (McGowan et al., 2015), whereas passive heating relies on external heat exposure and may produce different local and systemic physiological responses (Racinais et al., 2017). Therefore, comparisons between active and passive warm-up are difficult to interpret when protocols differ in thermal dose, movement specificity, and the performance assessment used.

Although recent research has demonstrated that passive warm-up via HWI can improve vertical jump performance, lower-limb power, and stretch-shortening cycle SSC function (Rodrigues et al., 2025a), these effects have not been directly compared with AWU. Consequently, it remains unclear whether passive warm-up can provide comparable or greater performance benefits than traditional AWU strategies. Furthermore, few studies have examined whether different warm-up strategies influence vertical jump tasks with distinct mechanical demands, including SJ which primarily assesses concentric lower-limb power, CMJ which relies on SSC function, and DJ which requires rapid SSC activation and RSI performance. Therefore, research is still needed to determine whether passive warm-up can produce performance enhancements comparable to AWU across vertical jump tasks requiring different neuromuscular and muscle contraction characteristics.

3.1 Aim and Hypothesis

The aim of this study was to compare the acute effects of passive and active warm-ups on vertical jump performance in physically active adults. Specifically, HWI was used as the passive warm-up strategy, whereas aerobic exercise combined with dynamic movements was used as the active warm-up strategy. Both warm-up conditions were compared with a control condition using thermoneutral water immersion. The interventions were performed before three vertical jump tests (i.e., SJ, CMJ, and DJ) which were used to assess concentric lower-limb power, slow SSC function, fast SSC function and RSI.

It was hypothesized that both passive and active warm-ups would produce improvements in vertical jump performance, whereas the control condition would show no improvement. Passive and active warm-ups were also expected to produce similar overall improvements because both strategies can increase muscle and core temperature, heart rate, blood flow, oxygen delivery, and glucose availability. However, the magnitude of improvement was expected to differ between jump types because the SJ, CMJ, and DJ involve different mechanical and neuromuscular demands. Specifically, jump height was expected to increase in the SJ, CMJ, and DJ following both warm-up conditions. Peak propulsive force during the SJ and CMJ was also expected to increase, although these changes may be less consistent than those observed in jump height. In addition, DJ reactive strength index was expected to increase, reflecting improved fast SSC function and reactive strength. Therefore, positive changes were expected across all three jump tasks, although the magnitude of these responses was expected to vary according to the specific performance variable and mechanical demands of each jump.

Chapter Four
Methods

Prior to participants recruitment and data collection procedures, this study was approved by the University of Waikato Human Research Ethics Committee (HREC(Health)2025#69).

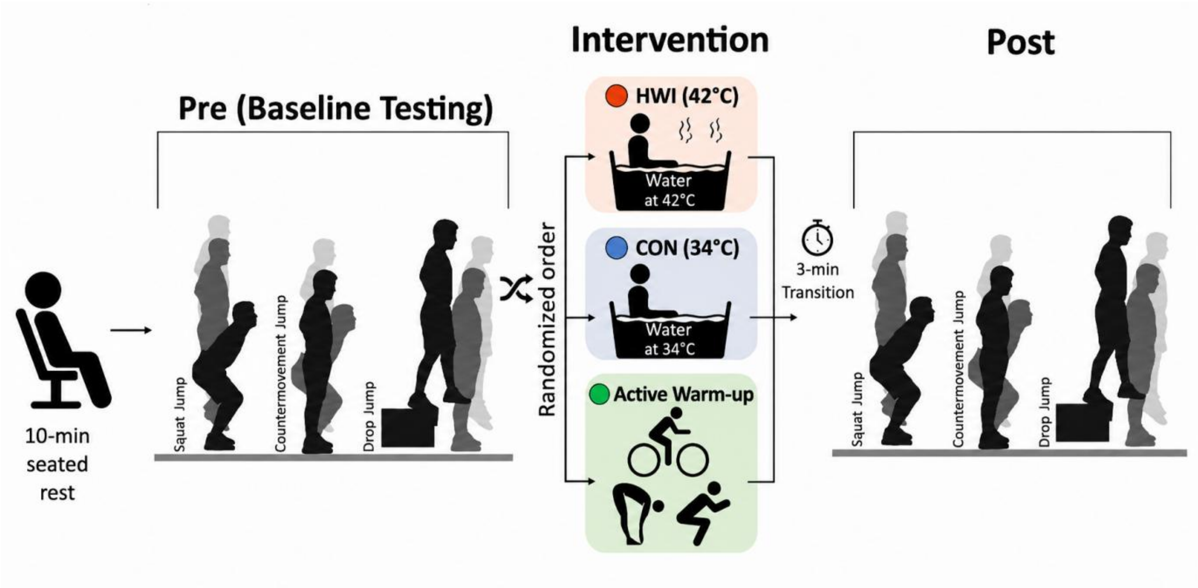
4.1 Participants

Twenty healthy and physically active individuals (15 males, 5 females; age: 25.9±4.5 years; stature: 177.9±9.5 cm; body mass: 82.7±22.6 kg; BMI: 26.1±7.7) completed the experimental protocol. All participants provided written informed consent after receiving a detailed explanation of the research design, objectives, testing protocols, and potential risks, as well as the associated risk mitigation strategies. To ensure a homogenous and safe cohort, participants were excluded if they met any of the following criteria: (a) medical conditions contraindicated by heat stress (e.g., multiple sclerosis, cardiovascular, or respiratory diseases); (b) history of lower-limb musculoskeletal injury; (c) use of medications known to alter thermoregulation; or (d) pregnancy. Throughout the experimental period, participants were instructed to maintain their habitual dietary patterns while adhering to specific pre-trial restrictions. Specifically, participants abstained from alcohol and caffeine for at least 24 hours prior to each testing session. Furthermore, they were required to avoid high-intensity resistance or aerobic exercise for the duration of the study to minimize confounding effects on performance outcomes.

4.2 Research Design

Figure 1

Overview of the Randomised Crossover Experimental Protocol



Following a randomized crossover design, participants attended three experimental sessions separated by a minimum washout period of ≥72 hours to ensure full recovery. Each visit commenced with 10 minutes of seated rest followed by a baseline (Pre) testing battery, including the squat jump (SJ), countermovement jump (CMJ) and drop jump (DJ). Participants then underwent one of three randomized interventions: (a) passive warm-up consisting of 60 minutes of hot-water immersion (HWI) at 42°C, (b) a control condition (CON) involving thermoneutral water immersion at 34°C for 60 minutes, or (c) a standardized active warm-up (AWU) protocol. A 3-minute transition period was established post-intervention for attire changes and preparation. Immediately following this transition, the vertical jump testing procedure was repeated (Post) to assess acute changes in performance (figure 1).

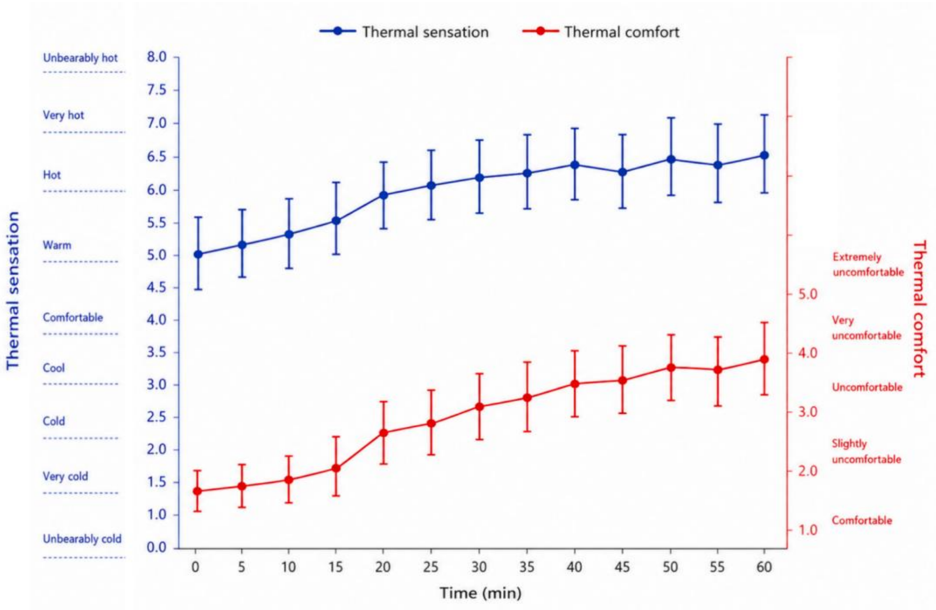
4.3 Procedures

4.3.1 Passive warm-up protocol

For the passive warm-up protocol, hot-water immersion was conducted in a bath with participants submerged to waist level for 60 minutes, following the lower-body immersion approach used by Rodrigues et al. (2025). Water temperature was manually regulated at 42 ± 0.2°C using a reference thermometer (C376-IC; Center Technology Corp., New Taipei City, Taiwan). To maintain the target water temperature, hot or cold water was added if the temperature fluctuated by 0.2°C, with excess water removed to ensure a consistent immersion depth at the waist. To prevent dehydration and improve thermal comfort, participants were permitted to drink water ad libitum, and an electric fan was utilized for the upper body during the immersion period. Participants rated their thermal sensation using the scale developed by Young et al. (1987) and their thermal comfort using the scale described by Velt and Daanen (2017). Ratings were recorded at the start of immersion and every 5 min throughout the 60-min protocol to monitor subjective thermal responses and participants' tolerance of the intervention (Figure 2).

Figure 2

Thermal Sensation and Thermal Comfort Responses During the 60-Min Immersion Protocol



4.3.2 Control condition

Similarly to the passive warm-up protocol, participants were submerged to waist level for 60 minutes in water maintained at 35 ± 0.2°C. Water temperature was manually regulated using a reference thermometer (C376-IC; Center Technology Corp., New Taipei City, Taiwan).

4.3.3 Active warm-up protocol

The session consisted of 15 min of cycling on a Wattbike (Wattbike Trainer; Wattbike Ltd., Nottingham, United Kingdom) at an RPE of 14 on the Borg 6–20 scale (Borg, 1998), consistent with a moderate-to-high intensity aerobic warm-up protocols shown to increase lower body muscle temperature and CMJ performance (Tsurubami et al., 2020). Power output was recorded every 3 min as an objective indicator of external exercise intensity, resulting in a mean power output of 127.5 ± 38.1 W. Heart rate was also monitored to reflect the physiological intensity responses of the active warm-up, with a mean value of 158.4 ± 7.3 bpm. Following cycling, participants completed dynamic lower-limb stretches, 10 bodyweight squats, and 10 submaximal CMJs in a standardized sequence. Dynamic stretching was included based on evidence of improved vertical-jump performance and muscle activation (Hough et al., 2009), while the progression from aerobic exercise to dynamic activities and practice CMJs was adapted from the warm-up structure used by O’Grady et al. (2021).

4.3.4 Vertical jump testing

Participants completed a standardized battery of vertical jump tests, including the SJ, CMJ, and DJ in the same sequence. To isolate lower-limb force generation and minimize the influence of upper-body momentum, participants were instructed to maintain their hands on their hips throughout all protocols, as arm swing has been shown to influence vertical jump performance (Harman et al., 1990). The SJ was performed from a static squat position without any countermovement; participants were required to jump vertically as explosively as possible upon a verbal command. For the CMJ, participants executed a rapid downward countermovement by flexing the hips, knees, and ankles, immediately followed by an explosive vertical jump, with instructions to maximize jump height. DJ assessments were performed from a 28-cm platform. Participants were instructed to maintain trunk stiffness upon landing to minimize ground contact time and emphasize reactive strength. For each assessment, three trials were completed with a minimum 60-s rest interval between attempts, consistent with previous reliability evidence for SJ, CMJ, and DJ-derived reactive strength index (RSI) measures (Flanagan et al., 2008; Markovic et al., 2004). The best trial for each type of jump was recorded for subsequent statistical analysis. All vertical jump tests were performed on a force plate (Bertec Force Plate; Bertec Corporation, Columbus, OH, USA). The analysed variables were jump height and peak propulsive force for the SJ and CMJ, and jump height and RSI for the DJ.

4.4 Statistical Analysis

Statistical analyses were conducted using jamovi (Version 2.7.28). Data normality was assessed using the Shapiro–Wilk test. Descriptive data are presented as mean ± standard deviation (SD). Baseline values were compared across conditions to determine whether pre-intervention performance differed between experimental sessions. Due to interindividual variability in vertical jump performance across testing days, changes from pre- to post-intervention values (Δ) were used as the primary outcomes. These change scores were compared via an ANOVA test across the passive warm-up via HWI, AWU, and CON conditions. Where a significant condition effect was observed, Bonferroni-adjusted *post hoc* comparisons were performed. Statistical significance was accepted at $p < .05$.

Chapter Five
Results

Baseline values for vertical jump performance outcomes are presented in Table 4. No significant differences were observed between conditions for any vertical jump test or performance variable (all $p > 0.946$).

Table 4

Change in Vertical Jump Performance Across HWI, AWU, and CON Conditions

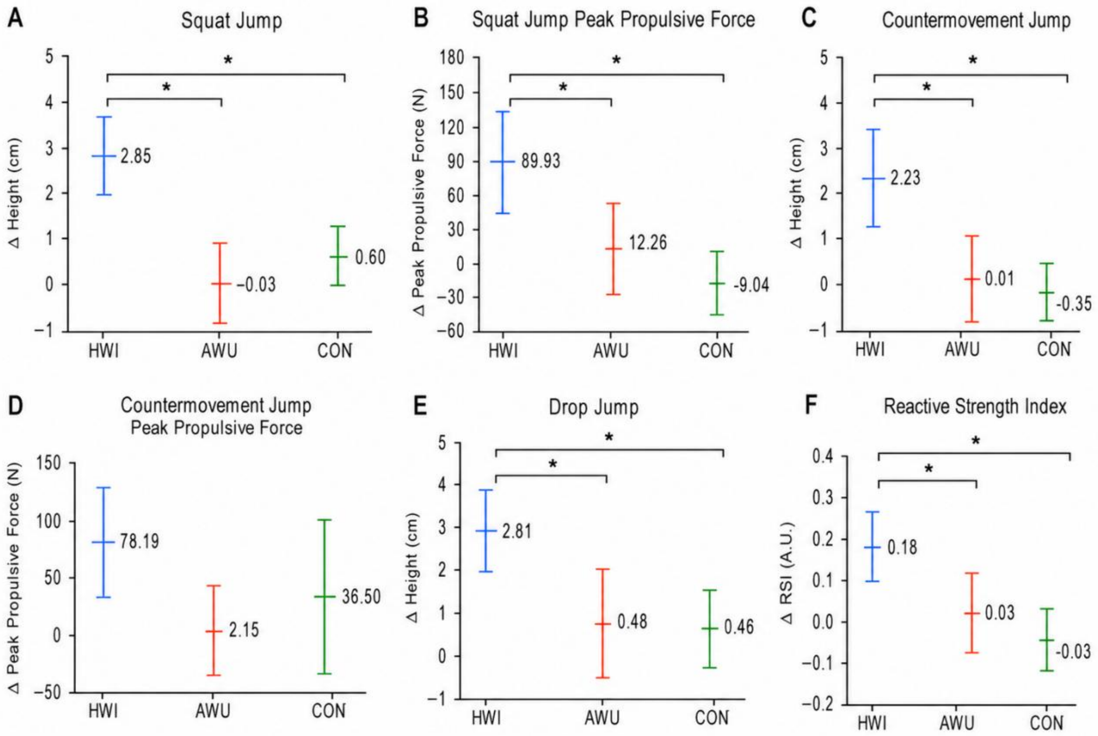
Outcomes	HWI	AWU	CON	*p*-value
SJ height (cm)	27.82 ± 7.91	28.32 ± 8.37	28.00 ± 8.42	.981
SJ PPF (N)	1883.24 ± 531.10	1889.72 ± 537.49	1874.71 ± 495.48	.996
CMJ height (cm)	32.51 ± 9.69	32.94 ± 10.09	32.79 ± 9.93	.990
CMJ PPF (N)	1819.3 ± 541.64	1818.9 ± 550.52	1811.8 ± 512.57	.999
DJ height (cm)	26.69 ± 7.04	26.84 ± 7.03	26.13 ± 7.46	.987
DJ RSI (A.U.)	1.06 ± 0.46	1.09 ± 0.53	1.07 ± 0.49	.946

Abbreviations: A.U., arbitrary units; AWU, active warm-up; CMJ, countermovement jump; CON, thermoneutral control; DJ, drop jump; HWI, hot-water immersion; PPF, peak propulsive force; RSI, reactive strength index; SJ, squat jump. Note: Data is presented as mean ± SD.

Following the warm-up interventions, significant condition effects were observed for SJ height ($p < .001$), SJ PPF ($p = .002$), CMJ height ($p < .001$), DJ height ($p = .006$), and DJ RSI ($p < .001$) (Figure 3). Bonferroni-adjusted comparisons showed that HWI produced greater positive changes than AWU and CON, respectively, for SJ height (both $p < .001$), SJ PPF ($p = .020$ and $p = .002$), CMJ height (both $p < .001$), DJ height ($p = .017$ and $p = .015$), and DJ RSI ($p = .011$ and $p < .001$). In contrast, changes in CMJ PPF did not differ significantly between conditions ($p = .108$), although the greatest mean increase was observed following HWI. No significant differences were observed between AWU and CON for any outcome.

Figure 3

Changes in Vertical Jump Performance Following HWI, AWU, and CON



Changes in squat jump height (A), squat jump peak propulsive force (B), countermovement jump height (C), countermovement jump peak propulsive force (D), drop jump height (E), and reactive strength index (F). The change scores (Δ) are presented as means ± 95% CI.

* Statistical difference between conditions (Bonferroni-adjusted post hoc comparison, $P < .05$).

Chapter Six
Discussion

This study aimed to compare the acute effects of passive and active warm-ups on vertical jump performance, and whether these effects differed across vertical jump tasks with different SSC demands, concentric power, peak power and RSI. The main finding of the present study was that HWI produced enhanced vertical jump performance across all three types of vertical jump tasks compared to both AWU and CON conditions, including SJ height and PPF, CMJ and DJ height, and RSI. In contrast, no significant differences were observed following AWU when compared to CON. Therefore, the hypothesis that passive and active warm-ups would produce similar improvements in vertical jump performance was not supported. These findings are largely consistent with Rodrigues et al. (2025), who reported that passive warm-up via HWI at 42°C improves CMJ height, lower-limb power, DJ height, and DJ RSI compared with thermoneutral water immersion. However, it did not support the findings from Tsurubami et al. (2020), who observed improvements in vertical jump performance following AWU via 15 minutes of aerobic exercise at moderate and high intensities.

Together, these findings support that 42°C HWI can acutely enhance explosive lower-limb performance across vertical jump tasks involving concentric power production (SJ height and PPF), SSC performance (slow SSC during the CMJ and fast SSC during the DJ), and RSI during the DJ. In contrast, the active warm-up protocol used in this study did not improve any vertical jump performance outcome compared with the control condition.

6.1 Passive warm-up and Vertical Jump Performance

The main finding of the present study was that HWI enhanced SJ height and PPF, CMJ height, DJ height, and DJ RSI, whereas AWU and CON produced no significant changes in any measured outcome. These improvements were observed across jump tasks involving no, slow, and fast SSC demands, suggesting that the effects of HWI were adapted to multiple types of explosive movement. However, CMJ PPF did not differ significantly between any conditions. This pattern indicates that the benefits of HWI were more consistently reflected in overall jump performance than in peak force measures and may therefore have involved changes in the timing or coordination of force production than an increase in peak force alone.

A plausible explanation for these improvements is that HWI increased lower-limb muscle temperature and accelerated the contractile processes required for explosive movement. Davies and Young (1983) found that increasing *triceps surae* muscle temperature shortened contraction and relaxation times, while vertical-jump height and power output were positively associated with muscle temperature. Similarly, Sargeant (1987) reported that 45 minutes of leg immersion at 44°C increased peak force and peak power during short-duration maximal cycling by approximately 11%, with greater temperature-related benefits evident at faster movement velocities. More recent neuromuscular studies provide further support for this mechanism. Rodrigues et al. (2021) showed that 90 minutes of lower-body HWI at 42°C increased muscle temperature by approximately 2.4°C and rectal temperature by approximately 1.0°C, accompanied by increases in early-phase voluntary and evoked rate of torque development. Half-relaxation time was reduced immediately after immersion, while electromechanical delay was reduced approximately 15 min later. Treigyte et al. (2024) similarly reported that passive heating produced a faster contractile profile, particularly through accelerated muscle relaxation, despite no corresponding improvement in maximal voluntary force. Rodrigues et al. (2023) also observed faster evoked twitch responses following 42°C HWI, although maximal voluntary torque and voluntary activation were temporarily reduced when core temperature was elevated. Collectively, these findings indicate that passive heating may improve how rapidly force is developed and relaxed rather than consistently increasing maximal force capacity, which is particularly relevant to vertical jumping because force must be produced within a limited propulsive or ground-contact period. Although the present study used a shorter 60-min immersion, the temperature kinetics reported by Rodrigues et al. (2020) suggest that this duration would be expected to increase deep vastus lateralis temperature by approximately 2.3–2.5°C and rectal temperature by approximately 0.8–1.0°C. The present protocol was therefore likely to have produced a meaningful lower-limb thermal stimulus capable of influencing temperature-sensitive contractile processes. At the same time, the effects of passive heating depend on the balance between local muscle heating and whole-body thermal strain, because substantial elevations in core temperature may impair voluntary activation and central neural drive, particularly during prolonged or fatiguing contractions (Morrison et al., 2004; Périard et al., 2014; Todd et al., 2005). The use of waist-level immersion at 42°C for 60 min was therefore intended to achieve substantial heating of the muscles involved in vertical jumping while leaving the upper body exposed to facilitate heat dissipation and limiting the additional core-temperature elevation, thermal discomfort, and participant burden associated with longer exposure. This interpretation is also consistent with Rodrigues et al. (2025), who reported improvements in CMJ height, lower-limb force and power, DJ height, and DJ RSI following 45 min of HWI at 42°C. Accordingly, the present 60-min protocol appears to have provided an effective thermal dose while limiting the greater systemic thermal strain likely to accompany a 90-min immersion.

The responses observed across the individual jump tasks provide further insight into how HWI may have influenced explosive performance. The improvements in SJ height and SJ PPF suggest that the benefits of HWI extended to concentric explosive performance with no SSC contribution. Because the SJ begins from a static position and eliminated countermovement and elastic energy storage, performance depends largely on the ability to generate force rapidly during the concentric propulsive phase. The observed improvements may therefore reflect temperature-related increases in contraction speed, early force production, and force transmission, consistent with previous evidence that passive heating can shorten twitch contraction and relaxation times, reduce electromechanical delay, and improve early-phase rapid force production (Rodrigues et al., 2021, 2023). Accordingly, the SJ response supports the interpretation that 42°C HWI can enhance the peripheral contractile processes required for rapid concentric force production.

The improvements in CMJ height, DJ height, and DJ-RSI indicate that the effects of HWI also extended to movements involving slow and fast SSC demands. The increase in CMJ height may partly reflect more effective concentric propulsion following the countermovement, as CMJ performance depends on both force production and the effective transition from the braking to the propulsive phase (Van Hooren & Zolotarjova, 2017). However, CMJ PPF did not differ significantly among conditions, suggesting that the improvement in jump height was not attributable simply to an increase in peak force. Instead, HWI may have influenced other characteristics of the force–time profile, including the rate or timing of force production, propulsive impulse, or coordination between the countermovement and take-off phases. The increases in DJ height and RSI further suggest that HWI may benefit reactive performance involving a fast SSC, in which force must be produced within a short ground-contact period (Markwick et al., 2015). Moreover, CMJ and DJ performance are influenced by muscle–tendon stiffness and compliance, elastic energy storage and return, preactivation, stretch-reflex behaviour, and inter-joint coordination (Komi, 2000; Van Hooren & Zolotarjova, 2017; Van Ingen Schenau et al., 1997). Thus, although HWI improved performance across tasks involving minimal, slow, and fast SSC demands, the relative contributions of muscular, tendon, and neural mechanisms cannot be determined from the variables assessed in the present study.

The proposed thermal explanation should also be interpreted cautiously because lower-limb muscle temperature was not measured directly. Although comparable 42°C HWI protocols provide a reasonable basis for expecting substantial muscle heating, the magnitude and time course of the thermal response achieved in the present participants remain uncertain. Thermal-comfort responses also varied between individuals, indicating that the same external heating dose was not perceived uniformly. However, because the relationships between thermal comfort, muscle temperature, and performance changes were not examined, perceptual variability cannot be assumed to explain the variation in force-related outcomes. Future studies should therefore combine direct measurements of muscle and core temperature with phase-specific jump kinetics, electromyography, muscle–tendon assessments. Overall, the present findings indicate that 42°C lower-body HWI can enhance explosive lower-limb performance across tasks with different SSC demands, most plausibly through temperature-related improvements in muscle contractile function, although the specific contributions of tendon and neural mechanisms remain uncertain.

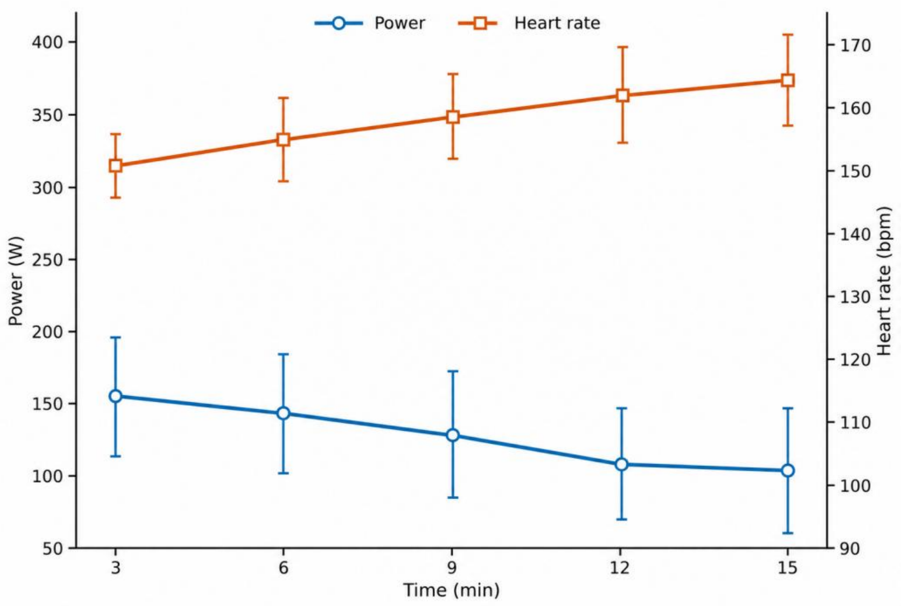
6.2 Active Warm-Up and Vertical-Jump Performance

It has been suggested that active warm-up may enhance short-duration explosive performance mainly through exercise-induced elevations in muscle temperature (Bishop, 2003b); however, whether comparable thermal responses induced through active and passive heating produce similar performance enhancements remains unclear. Tsurubami et al. (2020) reported that 15 minutes of treadmill running at 60% and 80% of VO_2 max increased *vastus lateralis* temperature by approximately 1.6°C and 2.3°C, respectively. Immediately following the warm-up, CMJ height increased by approximately 4.5 cm following exercise at 60% of VO_2 max and by approximately 5.0 cm following exercise at 80% of VO_2 max. The thermal response elicited by 15 minutes of treadmill running at 80% of VO_2 max was comparable to the approximately 2.4°C increase in deep vastus lateralis temperature observed after 60 min of lower-body hot-water immersion at 42°C in Rodrigues et al. (2020). These findings indicate that 15 min of aerobic exercise performed at 80% of VO_2 max can elevate muscle temperature to a magnitude similar to that achieved through 60 min of passive heating, while also improving CMJ performance. Nevertheless, because the studies differed in the heating method and the performance outcomes assessed, it remained unclear whether similar elevations in muscle temperature induced through active and passive warming would produce comparable improvements in vertical-jump performance.

Accordingly, the aerobic component of the present AWU was designed to approximate the muscle-temperature increase reported by Tsurubami et al. (2020), thereby enabling comparison with the thermal stimulus produced by the 60-min HWI condition. Participants completed 15 minutes of cycling on a Wattbike Trainer (Wattbike Ltd., Nottingham, United Kingdom) at an RPE of 14 on the Borg 6–20 scale, corresponding to an intensity between “somewhat hard” and “hard” (Borg, 1998). The duration was aligned with Tsurubami and colleagues; however, cycling replaced treadmill running, and intensity was regulated using RPE because VO_2 max was not directly assessed. Thus, the protocol was intended to produce a comparable thermal stimulus while differing primarily in the method of heating, although equivalent increases in muscle temperature could not be confirmed.

Figure 4

Power Output and Heart Rate Responses During the 15-Min Active Warm-Up Protocol



As shown in Figure 4, mean cycling-power declined progressively across the 15-min AWU, decreasing by approximately 32% from 153.5 ± 42.2 W at 3 min to 104.1 ± 42.2 W at 15 min. Conversely, heart rate increased from 151.0 ± 4.9 to 165.1 ± 9.5 beats·min^{-1}. The progressive reduction in external workload may have attenuated metabolic heat production and limited the sustained elevation in muscle temperature intended by the protocol. At the same time, the continued rise in heart rate despite declining power suggests an accumulation of internal physiological strain and a reduction in work capacity, which may indicate developing fatigue. Unlike Tsurubami et al. (2020), who used fixed running speeds individually prescribed relative to VO_2 max in trained male athletes, the present study applied an RPE-based intensity prescription to a more heterogeneous sample of physically active males and females. Differences in aerobic fitness and cycling tolerance may therefore have resulted in variable thermal and fatigue responses. The combination of a potentially reduced heating stimulus and accumulating fatigue may partly explain why AWU did not improve vertical-jump performance relative to CON. However, this interpretation remains tentative because muscle temperature, aerobic fitness, and metabolic markers of fatigue were not directly measured.

Active warm-up protocols for explosive tasks typically incorporate dynamic and task-specific activities after general aerobic exercise to supplement thermal effects with neuromuscular preparation (McGowan et al., 2015). In the present study, the 15-min cycling bout was followed by dynamic lower-limb stretching, 10 bodyweight squats, and 10 submaximal CMJs. Dynamic stretching was included because it may acutely increase peak twitch torque without impairing maximal voluntary force, thereby enhancing peripheral contractile readiness before maximal exercise (Vieira et al., 2025). The subsequent squats and submaximal CMJs were used as low-load, task-specific contractions to increase lower-limb activation, rehearse the flexion–extension pattern of jumping, and potentially facilitate rapid force production through potentiation-related mechanisms while limiting additional fatigue (Sale, 2002). However, AWU did not improve any vertical-jump outcome relative to CON, suggesting that any non-temperature-related facilitation provided by these components was insufficient to counteract the potentially attenuated thermal stimulus and fatigue accumulated during cycling.

6.3 stretch-shortening Cycle Demands and Jump-Type Specific Responses

The present study used the SJ, CMJ, and DJ to examine whether HWI and AWU influenced vertical jump tasks with no, slow, and fast SSC demands. Although all three jumps require rapid concentric force production, they differ in the physiological and mechanical factors that determine performance. The SJ begins from a static position and therefore provides a relatively direct assessment of concentric explosive function, whereas the CMJ and DJ additionally require effective use of the eccentric–concentric transition, elastic energy utilisation, muscle–tendon behaviour, and neuromuscular coordination (Van Hooren & Zolotarjova, 2017). These differences suggest that the same warm-up protocol may not influence each jump in the same way. HWI would be expected to act primarily through temperature-related improvements in contractile muscle function, which may be especially relevant to the SJ. In contrast, AWU may provide both thermal benefits and additional neural activation or movement-specific potentiation, which may be more relevant to CMJ and DJ performance, although these effects may be offset by fatigue (Fletcher, 2010). Therefore, the responses of the SJ, CMJ, and DJ should be considered in relation to both their specific physiological demands and the different mechanisms produced by HWI and AWU.

The increases in SJ height and SJ PPF following HWI indicate that the intervention improved concentric explosive performance and was accompanied by greater peak force during the propulsive phase. This finding is consistent with previous studies showing that

42°C HWI can substantially increase muscle temperature and accelerate early-phase force development and contractile responses (Rodrigues et al., 2021). Faster evoked contraction and relaxation responses following a comparable heating protocol provide further support for a temperature-mediated enhancement of peripheral contractile function (Rodrigues et al., 2023). Because SJ eliminates the contribution of a preceding SSC, faster force development and greater force expression during the concentric phase may translate relatively directly into increased PPF and jump height. Although previous research has shown that active warm-up can improve SJ performance, no significant changes in SJ height or SJ PPF were observed following AWU in the present study (Fletcher, 2010). One possible explanation is that the thermal stimulus generated by active exercise depends on the participant's ability to maintain the prescribed workload, whereas HWI provides a standardised external heat exposure independent of exercise capacity. The progressive decline in cycling power therefore suggests that some participants may not have generated or maintained a sufficient increase in muscle temperature to enhance concentric explosive performance. Although muscle temperature was not measured directly, the present findings indicate that 42°C HWI provided an effective thermal stimulus for improving the rapid expression of concentric force, whereas the physiological stimulus produced by AWU may have been more variable across participants.

Compared with the SJ, CMJ performance depends not only on rapid concentric force production but also on the development of muscle activation during the countermovement, the reduction of muscle–tendon slack, and effective force transmission before take-off (Van Hooren & Zolotarjova, 2017). Following HWI, SJ height increased by approximately 10.3%, whereas CMJ height increased by approximately 6.9%. This descriptive pattern may indicate that temperature-related improvements in contractile function were expressed more directly during the predominantly concentric SJ, whereas the CMJ response was additionally influenced by SSC-related mechanisms. However, the effects of passive heating on these mechanisms remain uncertain. Mornas et al. (2022) reported faster early force development but reduced passive muscle and active tendon stiffness following passive heating, suggesting potentially mixed effects on the muscle–tendon mechanisms involved in SSC performance. In contrast, Rodrigues et al. (2025) observed an approximately 10.1% increase in CMJ height following 42°C HWI and proposed that reduced muscle slack, improved force transmission, and greater elastic energy utilization may contribute to enhanced slow-SSC performance. The improvement in CMJ height observed in the present study therefore indicates that HWI can benefit a slow-SSC task; however, its numerically smaller response relative to the SJ does not establish whether SSC function itself was enhanced or whether the improvement primarily reflected enhanced concentric contractile function. Aerobic and dynamic warm-up may theoretically provide additional benefits through neural activation and rehearsal of the eccentric–concentric transition. Fletcher (2010) reported a greater improvement in CMJ than SJ following the fast dynamic component of an active warm-up, suggesting that neural stimulation and movement-specific preparation may be particularly relevant to SSC performance. However, neither CMJ height nor CMJ PPF improved following AWU in the present study, suggesting that these potential thermal and neural benefits may have been insufficiently stimulated or offset by fatigue accumulated during the aerobic component.

The DJ represents a fast-SSC task that requires rapid eccentric braking followed by the expression of force within a short ground-contact period (Flanagan & Comyns, 2008).

Performance is therefore influenced by rapid force development, preactivation, stretch-reflex behaviour, and the storage and return of elastic energy within the muscle–tendon unit (Komi, 2000). Following HWI, DJ height increased by approximately 10.5% and RSI by approximately 16.8%, indicating improvements across complementary measures of fast-SSC performance. Previous evidence suggests that DJ performance is temperature sensitive, with changes in muscle temperature influencing contraction timing, force production, and neuromuscular activation during the SSC (Oksa et al., 1996). Stretch-reflex responses during DJ performance have also been shown to vary with muscle temperature (Oksa et al., 2000). These findings provide a plausible basis for suggesting that the thermal stimulus induced by HWI improved the rapid expression and coordination of force following ground contact. Consistent with the present findings, Rodrigues et al. (2025) reported improvements in DJ height and RSI following 42°C HWI despite no change in vertical stiffness, and proposed that reduced muscle slack, improved force transmission, and enhanced elastic energy utilisation may have contributed to the response. However, the relevant neural and muscle–tendon mechanisms were not directly assessed in either study, and it therefore remains unclear whether the observed improvements reflected faster contractile function, enhanced SSC efficiency, or an interaction between these responses. In principle, AWU may provide additional benefits beyond muscle heating through movement-specific neural activation and post-activation performance enhancement. Fletcher (2010) reported a greater improvement in DJ than in CMJ and SJ following the fast dynamic component of an aerobic and dynamic warm-up. Poulos et al. (2023) similarly showed that appropriate task specific movement can acutely potentiate subsequent DJ performance, supporting the importance of balancing potentiation against fatigue. However, neither DJ height nor RSI improved following AWU in the present study, suggesting that the protocol may not have provided a sufficient fast-SSC-specific stimulus, or that any thermal and neural benefits were offset by fatigue accumulated.

The findings from the present study suggest that 42°C HWI enhances vertical jump performance across different tasks involving no, slow, and fast SSC demands. These improvements were most likely supported by temperature-related increases in the speed of force development and muscle contractile responses (Rodrigues et al., 2021, 2023). The improvements in CMJ and DJ performance further indicate that the effects of HWI were not restricted to predominantly concentric movements. However, because neural activation, reflex behaviour, muscle–tendon stiffness, muscle slack, and elastic energy utilisation were not directly assessed, it remains unclear whether HWI specifically enhanced SSC function or whether the observed improvements primarily reflected faster contractile force production. In principle, AWU may enhance jump performance by combining an increase in muscle temperature with movement-specific activation and post-activation performance enhancement. Nevertheless, these effects depend on an appropriate balance between potentiation and fatigue and may be influenced by the participant's strength, training experience, and ability to maintain the prescribed workload (Till & Cooke, 2009). Therefore, warm-up protocols shown to benefit trained athletes cannot be assumed to produce equivalent responses in a recreationally active population, and the intensity, volume, specificity, and recovery period of AWU should be adjusted according to participant characteristics.

6.4 Limitations and Future Directions

Several limitations should be considered when interpreting the present findings. First, lower-limb muscle temperature was not measured. Although the HWI protocol can reasonably be assumed to have increased tissue temperature, the magnitude of this increase and whether AWU produced a comparable thermal response remain unknown. This is particularly relevant because cycling power declined during AWU, suggesting that some participants may not have maintained the intended workload and may have experienced fatigue. Second, although HWI improved SJ, CMJ, and DJ performance, the present measures were insufficient to determine how heating affected the different components of slow- and fast-SSC performance. Finally, recruitment difficulties resulted in an uneven sample of 15 males and five females. The study was therefore not adequately powered to determine whether males and females differed in their thermal responses or subsequent improvements in jump performance.

Future studies should incorporate feasible measures of muscle temperature and physiological load to better verify and control the thermal stimulus produced by HWI and AWU. Establishing whether participants reach a comparable level of muscle heating before performance testing would allow a more rigorous evaluation of whether AWU provides additional benefits beyond heating or whether its effects are limited by fatigue. More detailed assessment of SSC performance, including variables reflecting the eccentric–concentric transition and fast-SSC function, would also help clarify the extent to which heating influences different jump tasks. In addition, larger and more sex-balanced samples, together with comparisons between participants of different training or performance levels, would help determine whether thermal and performance responses vary according to sex or physical capacity.

Chapter Seven
Conclusion

This study compared the acute effects of passive and active warm-ups on vertical jump performance via 60 minutes of HWI at 42°C, and a standardized active warm-up protocol via stretching exercises, submaximal squats and CMJ and 15 minutes of cycling. Following the warm-up interventions, HWI enhanced SJ height and peak propulsive force, CMJ height, and DJ height and RSI. Changes in CMJ peak propulsive force did not differ significantly between conditions, and no significant differences were observed between AWU and thermoneutral water immersion for any of vertical jump assessment outcomes. Therefore, the hypothesis that passive and active warm-up would produce similar improvements was not supported. Overall, a 60-minute session of HWI at 42°C enhances fast concentric force production, lower-limb peak power, SSC and RSI via vertical jump performance tests.

Chapter Eight
Scientific and Practical Significance

The present thesis provides further evidence that HWI can be an effective passive warm-up strategy for improving explosive lower-body performance. HWI produced positive changes in SJ, CMJ and DJ height, and SSC and RSI responses, whereas comparable improvements were not observed following AWU. These findings are consistent with previous evidence that increased muscle temperature can enhance rapid contractile function, reduce electromechanical delay, and improve rate-dependent force production (Racinais & Oksa, 2010; Sargeant, 1987; de Ruiter et al., 1999). The improvements observed across the SJ, CMJ, and DJ suggest that the benefits of HWI may extend beyond concentric-dominant performance to jump tasks involving slow- and fast-SSC demands. However, because SSC function was not measured directly, the specific mechanisms underlying the improvements in CMJ and DJ performance remain unclear.

These findings may inform the design of warm-up routines for healthy adults undertaking explosive lower-body activities. The absence of significant improvements following AWU suggests that the effectiveness of an exercise-based warm-up may depend on whether the protocol provides a sufficient thermal and neuromuscular stimulus without inducing excessive fatigue. In contrast, HWI applies an external thermal stimulus and is therefore less dependent on an individual's capacity to generate heat through muscular activity. HWI may consequently provide a useful passive strategy when the primary objective is to increase thermal readiness before explosive activity, particularly when active exercise is impractical, poorly tolerated, or likely to induce fatigue. Nevertheless, the 60-min immersion protocol used in the present study may limit its practical application. Future research should therefore determine the minimum effective combination of immersion temperature and duration and develop more efficient methods of assessing muscle temperature to confirm whether an adequate thermal stimulus has been achieved.

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Appendices

Appendix 1 – Ethics Approval

The University of Waikato
Private Bag 3105
Gate 1, Knighton Road
Hamilton, New Zealand

Human Research Ethics Committee
Professor Gary Wilson
Email: humanethics@waikato.ac.nz

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

29 September 2025

Conglin Li
School of Sport and Human Movement
Division of Health
By email: liconglin21@gmail.com

Dear Conglin,

HREC(Health)2025#69: Effects of Hot-Water Immersion on Vertical Jump Performance

Thank you for your responses to the Committee feedback.

We are now pleased to provide formal approval for your project.

Please contact the Committee by email (humanethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,

G. S. Wi

Professor Gary Wilson
Chairperson
University of Waikato Human Research Ethics Committee

Appendix 2 – Research Consent Form

Participant Consent Form

Project Title: The Acute Effects of Active warm-up and Water Immersion on Vertical Jump Performance

Researcher: Conglin Li (Master' s student, School of Health, Sport and Human Performance)

Supervisor: Dr. Patrick Rodrigues

Please read the following statements and tick each box if you agree:

☐ I have read and understood the Participant Information Sheet.

☐ I understand that this study involves three different warm-up protocols, and that some details may be withheld during the sessions to reduce bias (single-blind design).

☐ I understand that my participation is voluntary and that I may withdraw from the study at any time without needing to provide a reason.

☐ I understand that I may choose not to answer any question or not complete any activity if I do not feel comfortable.

☐ I understand that the information I provide will be treated as confidential and securely stored.

☐ I understand that the data collected may be used in academic publications or presentations, but my identity will not be revealed.

☐ I understand who to contact if I have any questions or concerns about the study.

☐ I agree to participate in this study.

Participant Name: ____

Participant Signature: ____________________________________

Researcher Name: Conglin Li

Researcher Signature: ____________________________________

Date: ____________________

Appendix 3 – Thermal Comfort Scale

THERMAL COMFORT SCALE

1.0	Comfortable
1.5	
2.0	Slightly uncomfortable
2.5	
3.0	Uncomfortable
3.5	
4.0	Very uncomfortable
4.5	
5.0	Extremely uncomfortable

Appendix 4 – Thermal Sensation Scale

THERMAL SENSATION SCALE

0.0	Unbearably cold
0.5	
1.0	Very cold
1.5	
2.0	Cold
2.5	
3.0	Cool
3.5	
4.0	Comfortable
4.5	
5.0	Warm
5.5	
6.0	Hot
6.5	
7.0	Very hot
7.5	
8.0	Unbearably hot