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Effect of Linear Polarized Near-infrared Light Irradiation and Light Exercise on Muscle Performance

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Abstract This study aimed to determine the effect of active warm-up by local muscle light exercise and passive warm-up by polarized light irradiation on skin and muscle temperatures and forearm muscle performance (muscle strength, power, endurance, and controlled force-exertion). Ten healthy males performed various grip tests before and after active (local muscle light exercise) and passive (linear polarized near-infrared light irradiation) warm-ups. An active warm-up involved intermittent gripping exercise (contraction: 1 second and relaxation: 1 second) for 10 minutes using a sponge. A passive warm-up consisted of polarized light irradiation to the forearm (superficial digital flexor) for 10 minutes (irradiation: 5 seconds and rest: 1 second). Skin and muscle temperatures were measured during both warm-ups. Skin and muscle temperatures increased significantly after 5 minutes of local muscle light exercise and after 10 minutes of polarized light irradiation. Temperatures were significantly higher after 6 minutes of local muscle light exercise than after 6 minutes of polarized light irradiation. There were no significant differences of muscle strength, power, and controlled force-exertion before and after either warm-up. Average force outputs in all conditions significantly decreased with exertion time, and at 30, 60, 90, and 120 seconds they were higher in both warm-up conditions than in the non-warm-up condition. In conclusion, both warm-ups may contribute to improve muscle endurance performance in the decreasing force phase.
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Introduction

A warm-up is performed to improve performance during primary exercise and to prevent injury. It advances cardiac performance, enhances intracellular Ca^{++} activity, and improves flexibility of soft tissue (muscle and tendon) and neural transmission (Bishop, 2003b). Although various warm-up methods have been proposed, they generally aim to stimulate cardiorespiratory and sympathetic nerves by increasing the heart rate to 120–130 beats/minute and to increase muscle temperature (Shellock and Prentice, 1985). Increasing muscle temperature results in improved muscle function and resilience of soft tissues (Yamamoto and Yamamoto, 1993). Previous studies have clarified that prior maximal voluntary isometric contractions (Gullich and Schmidtbleicher, 1996) and submaximal high-intensity contractions (2 repetitions of 20–90% of the 1 repetition maximum (1RM) load (Gourgoulis et al., 2003), 5 repetitions of 5RM intensity (Young et al., 1998)) can increase the rate of force development and jump height during repeated countermovement jumps and drop jumps (Gullich and Schmidtbleicher, 1996).

Muscle temperature can be increased not only by a general active warm-up (e.g., local muscle light exercise), but also by passive warm-up methods such as a hot pack or linear polarized near-infrared light (PL) irradiation. Recently, many researchers reported that PL irradiation to a muscle or meridian point results in a sensation of heat or irritation (Demura et al., 1994, 2000, 2002, 2006; Kobayashi et al., 1996; Wajima et al., 1996). This irradiation device was primarily developed to provide a therapeutic effect to odynolysis or resolution in clinical settings. It also creates physiological effects, such as an increase of blood flow or skin temperature (Kobayashi et al., 1996; Wajima et al., 1996). However, the effect of passive warm-up by PL irradiation on muscle performance has been not sufficiently examined. We hypothesized that a PL irradiation device may be useful as a support implement to improve muscle performance.

The aim of this study was to determine the effect of an active warm-up by local muscle light exercise and a passive warm-up by PL irradiation on skin and muscle temperatures and forearm muscle performance.

Methods

Subjects

Subjects were 10 healthy males [mean±SD age 21.3±0.7 yr, height 171.6±5.6 cm, body mass 65.6±9.0 kg]. They all were judged to be right-handed by a survey. All measurements were performed in the dominant hand. Written informed consent was obtained from all subjects after a full explanation of the experimental purpose and protocol. This study was approved by our University Committee on Human Research.

Materials

1. PL-irradiation device

PL-irradiation used spot-irradiation-type linear polarized near-infrared light (Super Lizer HA-30, Tokyo Medical Laboratory, Japan). This device emits linear polarized near-infrared light between 0.6 and 1.6 μm wavelengths up to 1800 mW power output (focus radius 10 mm). The irradiation unit can stimulate one point on the skin.

2. Skin and muscle temperature monitor

Skin and muscle temperatures were measured with a Coretemp thermometer (CM-210, Terumo, Japan). The temperature probe has two thermistors separated by a thermal insulator, with an electrical heating element mounted at the rear of the probe. The temperatures on the two sides of the insulating layer, as detected by the thermistors, are compared by a differential amplifier. The error signal is used to control the heater current in such a way as to achieve a situation in which no temperature gradient arises across the insulating layer and thus no heat flows out through this layer (zero-heat-flow). As long as a zero-heat-flow condition is maintained, the probe is equivalent to an ideal thermal insulator, i.e., heat loss from the skin surface beneath the probe is prevented and, after a sufficient time, the skin surface temperature will equilibrate with the deep tissue temperature. Therefore, this device can measure skin and deep tissue (muscle) temperature (Yamakage et al., 2002).

3. Measurement device of maximal muscle strength, endurance, and controlled force-exertion test

Maximal muscle strength, muscle endurance, and controlled force-exertion tests were performed using a digital hand dynamometer with a load-cell sensor (EG-100, Sakai, Japan). Each signal during grip tests was sampled at 20 Hz with an analog-to-digital interface and then relayed to a personal computer. The input digital data was immediately displayed on a screen to give feedback.

4. Muscle power test

Grip muscle power was measured using a dynamic grip measurement device with 30% of MVC load attached to the end of a wire (Yagami, Japan). A rotary encoder was attached at the pulley, and the rotational angle was measured in a rate per unit of time of the fixed pulley rated with the wire. The rotational angles were sampled with the recording device at 100 Hz by an analog-to-digital interface, and converted to the moving velocity of the load. The data were relayed to a personal computer.

Warm-up condition

1. Active warm-up by local muscle light exercise

An active warm-up included intermittent grip exercise for 10 minutes using a dishwashing sponge (nonwoven cloth and polyurethane resin sponge, 5×3×3 cm). To compress the sponge required a grip equivalent to 1 kg. Subjects grasped the machine rhythmically at a frequency of 30 grips/minute (interval time: 1 second).

2. Passive warm-up (PL irradiation)

A passive warm-up included PL irradiation on a forearm (superficial digital flexor) for 10 minutes. The irradiation was carried out with a cycle of 5 seconds of irradiation and 1 second of rest.

Experimental design and procedure

A within-subject design was used; that is, all subjects participated in both warm-up conditions (PL irradiation and local muscle light exercise warm-up) (Fig. 1). Maximal muscle strength, muscle power, and controlled force-exertion tests were carried out before and after both warm-up conditions. Muscle endurance tests before and after warm-up were not performed on the same day to remove the influence of fatigue (Fig. 1). Skin and muscle temperatures were measured during both warm-ups. The warm-up order for each subject was done by a counterbalance method to eliminate order effect bias.

All muscle performance tests were performed with the subjects seated in an adjustable chair. The grip width could be adjusted individually by a dial to achieve a 90-degree angle with the proximal-middle phalanges. The arm was supported by an armrest and was extended with the forearm in a horizontal position and the hand in a semi-pronated position. Muscle strength was defined as the peak force value measured by load-cell. Muscle power was defined as the peak power value while explosively pulling a bar held between the second digital joints without the thumb. The ability to control force-exertion was defined as the error value for 20 seconds between the subject's force output and the changing target force bar (changing range: 5–25% MVC, changing frequency: 0.3 Hz) (Nagasawa et al., 2000). Subjects tried to fit the exertion force to a changing target value appearing on the display. Rhythmic repeated grip with 30 grips$\cdot$min^{-1} for 6 min (interval times 2 seconds) was measured to evaluate muscle endurance. Muscle endurance was defined as the average peak force output every 30 seconds for 6 minutes.

The temperature probe was attached to a midportion of the superficial digital flexor. After skin and muscle temperatures became stable, they were measured during and after a warm-up (12 minutes).

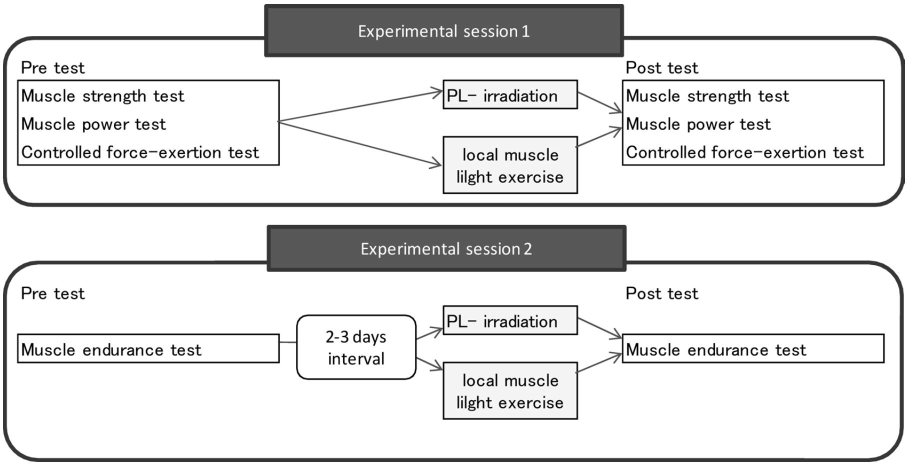

Fig. 1 Experimental protocol.
Subjects participated in both conditions (Within-subject design)

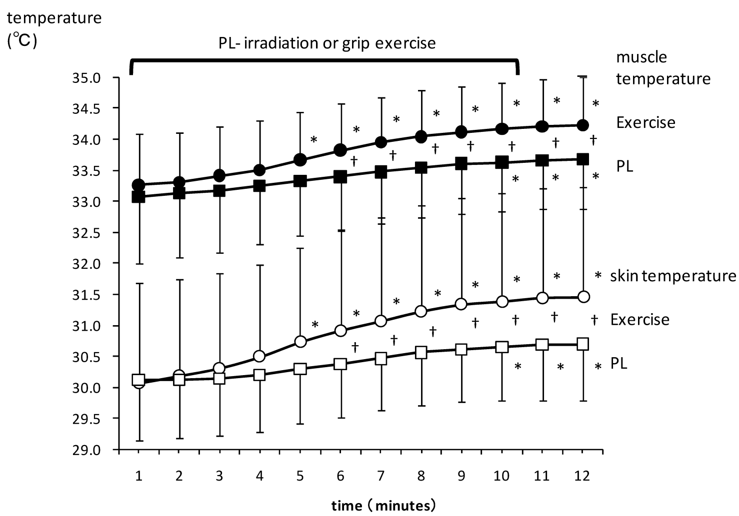

Fig. 2 Changes of skin and muscle temperatures during PL-irradiation and local muscle light exercise.
*: Temperature was significantly higher than that at 1 minute.
†: Temperature was significantly higher after local muscle light exercise than after PL irradiation

Data analysis

Average skin and muscle temperatures were calculated every 1 minute. Two-way repeated measures ANOVA was used to reveal changes of skin and muscle temperatures and the differences of muscle performances (muscle strength, muscle endurance, muscle power, and controlled force-exertion). Multiple comparisons were performed with Tukey's HSD method. The probability level of 0.05 was indicative of statistical significance.

Results

Figure 2 shows the changes of skin and muscle temperatures during both warm-up conditions. From the results of two-way ANOVA (warm-up condition×time), there were significant differences in interaction factors. Skin and muscle temperatures increased significantly after 5 minutes of local muscle light exercise and after 10 minutes of PL irradiation. They were significantly higher after 6 minutes of local muscle light exercise than after 6 minutes of PL irradiation.

Table 1 shows the results of two-way ANOVA (warm-up condition×before and after warm-up) for muscle strength, muscle power, and controlled force-exertion before and after warm-up. There were no significant differences in any parameters.

Figure 3 shows a time-decreasing curve by average peak force outputs every 30 seconds in non-warm-up and both warm-up conditions. From the results of two-way ANOVA (warm-up condition×exertion time), there were significant differences in warm-up condition and exertion time. Average force outputs in all conditions significantly decreased with exertion time, and were higher in both warm-up conditions

Table 1 The results of two-way ANOVA (warm-up condition×before and after warm-up) for muscle strength, muscle power, and controlled force-exertion before and after warm-up

	Before		After		Two-way ANOVA		
	PL-irradiation Mean SD	Light exercise Mean SD	PL-irradiation Mean SD	Light exercise Mean SD	warm-up F	time F	Interaction F
Muscle strength (kg)	48.9±3.4	49.2±4.8	48.3±2.8	49.3±4.6	0.52	0.18	0.85
Muscle power (W)	21.4±3.7	21.5±3.2	20.3±4.0	21.6±3.1	1.85	1.72	2.61
Controlled force-exertion (kg)	297.8±63.1	307.6±41.1	288.3±64.0	281.4±40.6	0.02	3.60	1.63

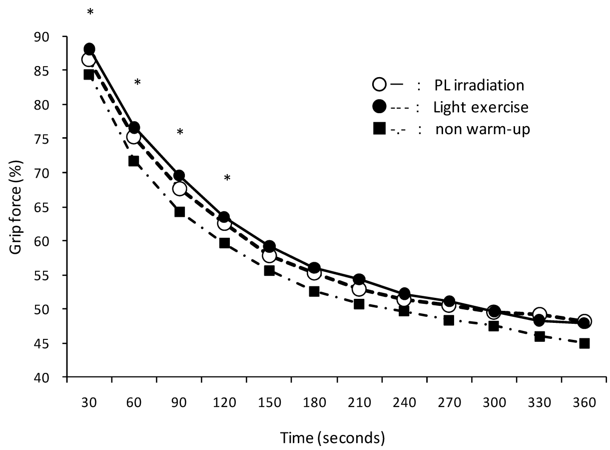

Fig. 3 The time-decreasing curve of average peak grip force output every 30 seconds in non-warm-up and after both warm-up conditions.
*: Grip forces were larger after PL-irradiation and light exercise warm-ups.
Grip force in all conditions significantly decreased with exertion time.

than in the non-warm-up condition at 30, 60, 90, and 120 seconds.

Discussion

Generally, stretching has been used to improve flexibility, but the improvement of flexibility also requires increased muscle temperature to improve the resilience of the soft tissues (Yamamoto and Yamamoto, 1993). Local muscle light exercise such as jogging increases muscle temperature, heart rate, muscle blood flow, and body temperature. It has been reported that PL irradiation increases muscle and skin blood flow and skin temperature (Kobayashi et al., 1996; Wajima et al., 1996). PL irradiation can provide light and heat stimulation to the body in a short time because of its improved light output compared to the helium neon laser and the semiconductor laser similarly used in clinical settings.

PL irradiation is very practical because anyone can easily provide treatment (Bishop, 2003a). If PL irradiation can increase muscle temperature similarly to local muscle light exercise, it may be an effective method to improve muscle performance. PL irradiation can either be applied directly to a target region (Demura et al., 2000, 2002, 2006) or near the stellate ganglion area related to body temperature control (Ide et al., 2007; Lee et al., 2006; Nakase et al., 2004; Wajima et al., 1996). The latter irradiation method was unable to increase the skin or muscle temperature of distal points (Ide et al., 2007; Lee et al., 2006; Nakase et al., 2004). Hence, this study used the former irradiation method.

In this study, skin and muscle temperatures during local muscle light exercise significantly increased (1.5±0.8 and 1.1±0.6 degree) after 5 minutes. On the other hand, they significantly increased (0.6±0.2 and 0.8±0.5 degree) after 10 minutes of PL irradiation. Both temperatures were significantly higher in local muscle light exercise than in PL irradiation, but the muscle temperature tended to be higher than the skin temperature in PL irradiation. The wavelength of PL irradiation (0.6–1.6 μm) allows for heat stimulation deeper into the body (Yamazaki et al., 2003).

There were no significant differences of muscle strength, muscle power, and controlled force-exertion before and after either warm-up. Many researchers (Gullich and Schmidtbleicher, 1996; Gourgoulis et al., 2003; Young et al., 1998) reported that warm-ups of maximal isometric contraction and maximal or high-intensity dynamic exercise can enhance dynamic muscle performances such as jump height. The disagreement of our study and the above previous studies may be due to differences in the following two points.

First, the main exercises included in the latter studies were dynamic muscle movements involving a stretch-shortening cycle. Many previous studies reported that an active or passive warm-up improved the range of motion (Demura et al., 2000, 2002, 2006; Matsuzawa et al., 1996; Wiktorsson-Moller et al., 1983). The stretch-shortening cycle can be used efficiently for improvement of flexibility. Moreover, the improvement of the resilience of the soft tissues with increased muscle temperature contributes to dynamic muscle contraction rather than static muscle contraction.

Second, the increase of muscle temperature with active and passive warm-up in this study may have been relatively low. Although both warm-ups (sponge gripping and PL irradiation) were performed in 10-minute segments, the muscle temperature increased by 1.1±0.6 and 0.8±0.5 degrees, respectively. Davies and Young (1983) reported that a muscle temperature increase of 2.5–3.0 degrees from rest was an optimal state for muscle contraction. This increase in muscle temperature decreases muscle stiffness and improves the force-velocity relationship (Binkhorst et al., 1977; Bishop, 2003b; Febbraio et al., 1996; Ranatunga et al., 1987). Moreover, French et al. (2003) suggested that a warm-up including a heavy load may induce a high-frequency stimulation of motor neurons and enhance motor neuron excitability. This result improves the rate of force development (Sale, 2002; Vandenboom et al., 1993). In other words, active warm-up with local muscle exercise may improve muscle performance (i.e., strength and power) if the warm-up protocol is set at a higher intensity level. However, it is difficult to change the protocol of passive warm-up by PL irradiation because the irradiation output power (1800 mW) used in this study was marginal. Therefore, the passive warm-up by PL irradiation may not be able to improve muscle performance.

On the other hand, muscle endurance performance tended to improve with the active and passive warm-ups selected in this study. Both warm-ups controlled a decrease of force output up to 120 seconds after starting muscle contraction, which is the phase of marked decline in force. Because morphological changes of skeletal muscle are not found before or after warm-up, the improvement of muscle endurance is thought to depend on an increase of oxygenation and dilation of blood vessels by increasing core temperature and improving the utilization efficiency of oxygen within muscle cells (Kudoh and Matsuki, 2000). Nakada et al. (2005) examined muscle oxygenation kinetics using the same grip test in this study (rhythmic repeated grip with 30 grips $\cdot$ min^{-1} for 6 minutes), and reported that oxygen was not satisfactorily supplied to active muscle until 120 seconds because of the obstruction of blood flow caused by an increase in the intra-muscular pressure. Moreover, they also reported that muscle oxygenation kinetics enters the state where oxygen is satisfactorily supplied to active muscle over 120 seconds because of the exercise hyperemia with resumption of blood flow. Therefore, it is inferred that the increasing blood flow volume before the endurance test by both warm-ups resolves the lack of oxygen supply until 120 seconds, and results in gradual force decreasing.

Interestingly, there were significant differences in the increases of skin and muscle temperature by active and passive warm-up in this study, but both endurance performances (up to 120 seconds) improved to a similar extent. The increases of skin and muscle temperature influence the increase of muscle blood flow, and it promises an increase of oxygen supply to active muscle as stated above. However, it is possible that the increase of oxygen supply is sufficient by passive warm-up in this study.

In conclusion, skin and muscle temperatures increased significantly with the active and passive warm-ups selected in this study. However, muscle strength, muscle power, and controlled force-exertion performance did not improve with either warm-up. Both warm-ups may contribute to improved muscle endurance performance in a marked decreasing force phase.

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