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Effect of heat and cold on tendon flexibility and force to flex the human knee

Authors' Contribution:
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Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
Literature Search F
Funds Collection G

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Background: It is commonly believed in medicine that using heat will increase the distensability and flexibility of soft tissue. If true, increased flexibility would be a positive factor to reduce injuries in sports. However, cold should have the opposite effect and is often used to treat sports injuries. This study was accomplished to quantify the effect of heat and cold on the force needed to flex the knee and laxness of the anterior and posterior cruciate ligaments.

Material/Methods: The present study examined 20 male and female subjects to determine if heat would increase extensibility of the anterior and posterior cruciate ligaments of the knee and reduce the force needed to flex the knee. Cold exposure was examined to see if it would have the opposite effect. There were 4 experiments in the series: The first was a room temperature series; the second was a series where cold was applied with an ice pack for 20 minutes; in the third, hydrocollator heat packs were applied for 20 minutes; and in the fourth, ThermaCare heat wraps were applied for 4 hours on the quadriceps and knee. Tendon extensibility was measured with a KT2000. The force for flexing the knee was measured by passive movement being applied (CPM) to the knee through 30° and the force required to move the leg was measured.

Results: The results show that the anterior and posterior cruciate ligament flexibility increased and the force needed to move the knee decreased with heat by about 25% compared to cold application.

Conclusions: Heat is beneficial in increasing muscle and ligament flexibility and may help reduce athletic injuries, but cold treatment may have the opposite effect.

Key words: heat • tissue elasticity • sex differences • muscle • tendon

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Background

Athletic injuries are common in the adult population [1,2]. It is generally assumed that a warm up, by increasing tissue temperature, will increase tissue distensability and reduce the incidence of injury [3,4]. These warm-ups involve many modalities and can include stretching, heat, changes in tissue temperature by exercise, and even mental conditioning [3,4]. However, it is not clear which factor or factors actually reduce injury in the athlete. This is especially true in female athletes, whose biomechanics and hormonal influences make them very susceptible to anterior cruciate ligament tears and ankle injuries [5–8].

Heat is very commonly used before exercise [9]. One advantage is that by increasing tissue metabolism the muscle is prepared for the metabolic challenge of exercise [9,10]. Heat also increases glycogen resynthesis and muscle recovery [10]. Heat is also cited as increasing flexibility and thus reducing the chance of injury, and reducing energy cost of muscle contraction by reducing internal friction [11,12]. Internal energy costs are reduced by warming muscle, but many of these studies have been done in animals and very few in humans. There is only limited evidence that heat helps tissue stretching in humans. Further, when heat is used, there is no previous evidence of the effects of heat on the tendon or muscle itself, commonly referred to as the series and parallel elastic components in muscle [13].

In rat tendons, applying force to collagenous tissues causes stretching, which is greatly aided by heat [14]. The response of stretch receptors in the cat are also increased by heat [15]. The mechanism of the changes in the series' elastic component is partly due to unwinding of the actin filaments in muscle due to stretch and partly due to collagen relaxation [11,12]. There is also rotation of the actin filaments with heat [11]. While there is some evidence that heat increases muscle flexibility in humans, there has been no study of where the benefit is (parallel or series elastic components, or how long the benefit lasts) [16–19]. This was the purpose of the present investigation. We examined 2 heat modalities: a slow heat modality and a fast heat modality. We also examined cold packs to see what effect they might have on tissue elasticity, because cold is commonly used with injuries during sporting events.

Material and Methods

Study subjects were 12 males and 8 females, ages 20–30, with no diagnosed tendon or other orthopedic injuries. Subjects were non-athletes and of normal body weight. The subjects were divided into 2 groups of 10 each. Group 1 participated in the first series of experiments and Groups 1 and 2 both participated in the second series. All procedures and protocols were approved by the Institutional Review Board of either Loma Linda or Azusa Pacific University. The general characteristics of the subjects are shown in Tables 1 and 2.

Methods

Ligament elasticity

Elasticity of the anterior and posterior cruciate ligaments was measured by a kinematic knee device that is commercially produced and has been validated in numerous studies. The device was the Medmetric KT2000 (Medmetric corporation, San Diego, California). The subject lay supine with the angle of the knee at 30° (Figure 1). A strain gauge measured the force necessary to generate an anterior/posterior glide of the proximal end of tibia on the femoral condyles, thus generating a force curve of elasticity of the anterior (ACL) and posterior (PCL) cruciate ligaments.

A foot positioning device and thigh strap were used to position the subject. Force was applied for the anterior cruciate ligament at 15, 20, and 30 lbs. (66.6, 88.8, 133.2 newtons). It was applied at 20 lbs. (88.8 newtons) for the posterior cruciate ligament. As force was applied, the force and displacement controlled an x-y plotter to record the ligament elasticity. The device has been well validated and reported [20–22].

Table 1. General characteristics of subjects in Group 1.

	Age	Height	Weight	BMI
Mean	26.0	182.7	79.8	23.8
SD	4.2	5.3	12.7	2.8

Table 2. General characteristics of subjects in Group 2.

	Age	Height	Weight	BMI
Mean	24.3	175.0	69.1	22.3
SD	1.7	10.7	15.4	3.0

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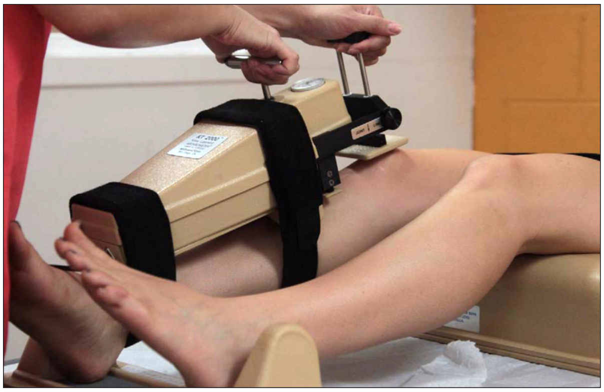

Figure 1. Typical placement of the leg to measure knee ligament laxness.

Figure 2. The linear actuator.

Force to flex the knee (FK)

The force to flex the knee was measured for the quadriceps muscle (FK). The subject was in the seated position with the leg free to hang at an initial angle of 90° with the foot off of the floor. A linear actuator was connected through an ankle strap to passively move the knee through 25° of flexion (Figure 2). The force needed to move the knee was measured as a measure of the flexibility and elasticity of the quadriceps muscle and its tendons. The force measurement was accomplished with a load cell in series with the linear actuator. Resistive strain gauges (350 ohms) were arranged as a Wheatstone bridge. The bridge output was amplified and conditioned with a DAC100 strain gauge amplifier with a gain of 500 (BioPac Systems, Goleta, CA). The amplified output was digitized at 2000 hertz with a resolution of 24 bits on an MP150 BioPac data acquisition system (BioPac Systems, Goleta, CA). A goniometer measured the angle of the knee to calculate the force needed per° moved (Figure 3). The goniometer used a ruby bearing 360° 5000 ohm potentiometer. Its output was amplified and digitized by the BioPac system as described above.

Since different legs had different masses, the data was normalized by dividing the force required to move the leg per degrees of movement at the knee and dividing this number by the body weight.

Figure 3. Subject sitting on the platform and connected to the linear actuator. The electro goniometer is shown on the knee.

Procedures

For each subject, baseline ligament flexibility and the force to move the lower leg were measured, followed by 2 series of experiments. The purpose of the first experimental series was to see what changes might occur in the quadriceps response to forced movement and the elasticity in the anterior and posterior cruciate ligaments during 4 hours of heat exposure with ThermaCare heat wraps. The speed of movement was also varied. Thermacare heat wraps are slow-warming wraps. In contrast, fast-warming or cooling sources are used clinically. We wanted to see if there was steady-state heating after 4 hours, which would allow us to compare this slow response heating to standard high temperature and low temperature modalities that are only applied for 20 minutes in therapy. We also needed to evaluate the effect of speed of flexion of the knee to set the speed for flexion in the second series of experiments. From the first series of experiments, a steady-state heat response was found after 4 hours; therefore, in the second series of experiments in Group 2, ThermaCare

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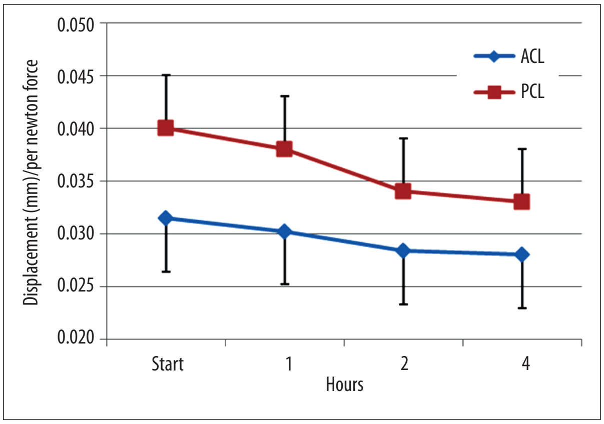

Figure 4. The displacement of the tibia per newton of applied force for the anterior (AC) and posterior (PC) cruciate ligaments in 10 subjects ± the standard deviation. Data were collected at rest, and after 1, 2, and 4 hours after heat pack application.

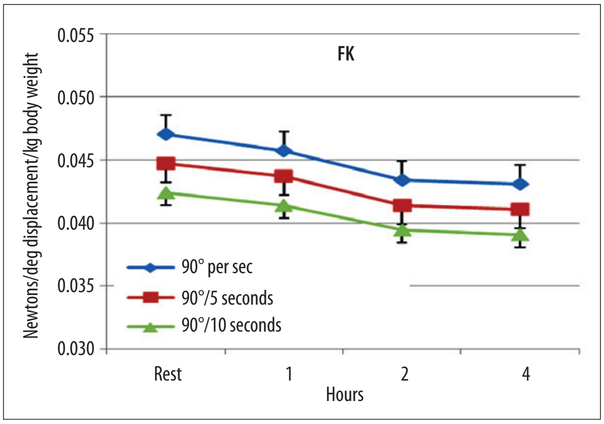

Figure 5. Newtons of force per degree movement of the quadriceps per kg body weight to move the knee into flexion. The graph shows the mean for 10 subjects ± the standard deviation. Data were collected at rest, and after 1, 2, and 4 hours of heat pack application. Three speeds of movement were tested: 90°/sec, 90°/5 sec, and 90°/15 sec.

heat wraps were applied for 4 hours and the data was compared to 20-minute hydrocollator heat pack applications and 20-minute cold pack applications.

Therefore, the subjects were divided into 2 groups. In Group 1, heat was applied to the quadriceps muscle and knee with a ThermaCare heat wrap for 4 hours. ACL and PCL flexibility and the force to move the lower leg were measured after 1, 2, and 4 hours of Thermacare heat application. Three speeds were used for quadriceps flexibility – 90° per second, 90° per 5 seconds, and 90° per 15 seconds – and force was recorded in terms of the position of the muscle to see if there was a major difference in the movement of the lower leg with speed of movement. Based on these results, in Group 2, only 1 speed of movement was used for the quadriceps muscle – 90° in 15 seconds. In this group, tendon elasticity and force to move the quadriceps muscle were measured either after 4-hour application of ThermaCare heat wraps, 20-minute application of hydrocollator heat packs, or 20-minute application of ice packs. The ice packs and hydrocollator heat packs were separated from the skin by 6 layers of towels. This series therefore examined the effect of cold compared to slow heat and rapid heat changes on the skin above the knee and muscle.

Statistical and data analysis

This was a longitudinal study. Data was analyzed by paired t tests, means, and standard deviations. ANOVA was used to compare groups. The level of significance was $p<0.05$.

Results

Series 1 – the effect of heat on ACL, PCL, and FK

The relationship between the force required to displace the tibia as a measure of anterior and posterior cruciate ligament elasticity is shown in Figure 4 for the 10 subjects in Group 1. As shown in the figure, the application of ThermaCare heat wraps caused an increase in the laxness of the anterior and posterior cruciate ligaments. There was a small increase after 1 hour, which peaked at 4 hours. The data at 2 and 4 hours were not significantly different. For both ACL and PCL there was a significant difference from the start data at 1 and 2 hours but no difference between hours 2 and 4 hours (ANOVA $p<0.05$).

For the force to move the knee through flexion (FK), the data is shown in Figure 5.

As shown in Figure 5, with increasing time that the heat packs were applied, there was less force needed to flex the knee. For increasing the rate of movement at any time period, the force required to flex the knee was greatest for the fastest movement (the difference between the 3 conditions was significant, ANOVA $p<0.05$). The greatest reduction in force was after the second hour of heat pack application.

Series 2 – the effect of cold, rapidly applied and slowly applied heat

Since there was steady-state elasticity after 4 hours with ThermaCare heat wraps, this series of experiments then compared a slow heat source applied for 4 hours using ThermaCare heat wraps *versus* standard therapy sessions using cold and hydrocollator heat applied for 20 minutes.

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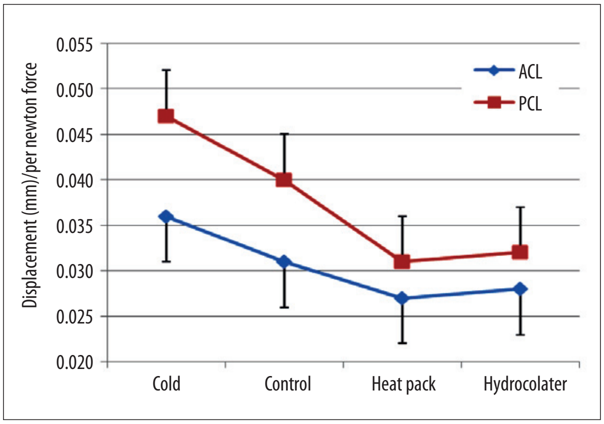

Figure 6. The displacement per newton force for the anterior (AC) and posterior (PC) cruciate ligaments in 10 subjects ± the Standard Deviation. Data was collected at room temperature and 20 minutes after cold pack application or 20 minutes after application of hydrocollator heat packs or 4 hours after application of ThermaCare heat wraps.

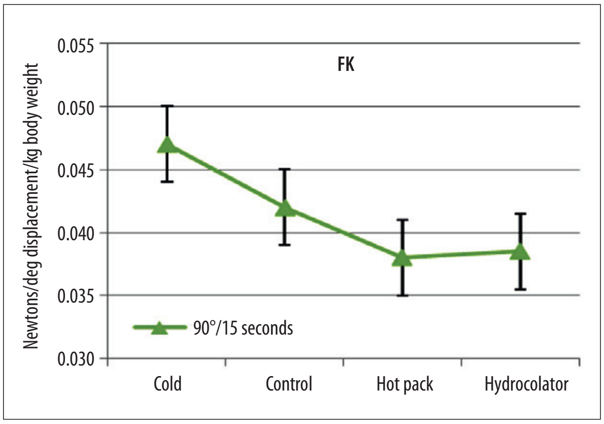

Figure 7. Newtons of force per degree movement of the quadriceps per kg body weight to move the knee into flexion. The graph shows the mean for 10 subjects ± the standard deviation.

The relationship between the force required to displace the tibia to stretch the anterior and posterior cruciate ligaments is shown in Figure 6 for the 10 subjects in Group 2. As shown in this figure, cold caused an increase in force needed to stretch the anterior and posterior cruciate ligaments; whereas hydrocollator heat packs and ThermaCare heat wraps increased flexibility. The difference between the response to cold and both heat modalities was significant ($p<0.05$). For the anterior cruciate ligament, only the 132 newton data are shown. The 89 newton data followed a similar course. Female subjects had significantly greater movement of the tibia at the same force. Thus, the displacement per unit force was significantly higher – by 21% for the ACL and 16% for the PCL for women compared to men ($p<0.05$).

For the forces to passively move the knee (FK), the data is shown in Figure 7.

With increasing application of warmth, there was a linear decrease in the force needed to move the knee, showing a reduction in tissue elasticity with heat (Figure 7). There was no difference between the ThermaCare slow heat data and the hydrocollator heat pack data. There was no significant difference between men and women when data were normalized by body weight ($p>0.05$). When examining the raw data not corrected for mass of the men's legs, it took more force to move the men's legs than the women's legs.

When the force data was analyzed at a knee angle of 20° of flexion compared to relaxation, a hysteresis curve was established. The difference between the force for flexion and passive relaxation was 18.4±6.3 newtons after cold packs, 12.8±4.3 newtons with the leg at room temperature, and averaged 8.9±3.7 newtons after the 2 heat pack applications, showing a reduction in stiffness with heat.

Discussion

Heat is commonly used in some form before exercise [3]. The temperature of muscles and ligaments is normally below that of the core temperature [23-25]. The core temperature is protected at about 37°C [26]. But, since almost 2/3 of all calories of food ingested result in the production of heat, over a million calories a day needs to be dissipated to keep the core cool. The core is classically defined as the brain and heart [25]. The intestinal track is usually warmer than the core; in the digestion of food, it produces heat and may be up to 2°C above that of the core [27]. Shell tissues (e.g., arms and legs), are used as a radiator to remove heat from the intestines, active muscles, and the core [28,29]. The shell tissues are kept at least 6°C below the core so that heat can move from the core to the shell and be removed from the body [30–32]. Skin temperature is thus typically 31°C on the arms and legs [28,30,32]. For the tissues below the skin, temperature varies by depth and location from the core. Generally, the further deep tissues are away from the central body, the cooler they are [32,33].

It is no surprise then that heat is commonly used before exercise. The simplest way of heating these deep shell tissues is by light exercise. Light exercise raises the blood flow to muscle and the temperature of muscle rises toward that of the core [2,30,32,33]. But other tissues such as the knee and its ligaments can only be heated effectively externally [26,34,35]. This is also true for the ankle. Here, external heat may be of great benefit.

While there is a consensus on the use of heat for increasing ligament and muscle stretching prior to exercise as a means

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of reducing injury [36], there is little evidence that this really works. Logically, since ligaments and tendons are elastic structures, they should be more flexible with heat. Increasing temperature increases flexibility of knee ligaments (anterior and posterior cruciate) and there is a substantial change in tissue elasticity. In previous studies, a warm-up before athletic events has been shown to substantially reduce athletic injuries [36–38]. The assumption is that these soft tissue injuries are reduced by heat by increasing the elasticity of tendons and ligaments [37,38]. There is, however, no direct evidence for this hypothesis. Previous studies on heat and ligament elasticity have dealt largely with human cadavers or rat tendons. For example, when rat anterior cruciate ligaments and quadriceps muscle tendons were heated from room temperature to near core, both showed an increase in elasticity, with the largest being in the hamstring tendons [39]. The quadriceps tendons did not include the muscle itself. In the present investigation, the increase in elasticity of the anterior cruciate ligament was similar to rat data and the present investigation, but the hamstring rat data was more elastic than the whole quadriceps and tendons seen here. However, in humans the tension in grafts of the hamstring showed an increase in elasticity by about 20% when the tendons warmed from operating room temperature to body temperature after the graft was implanted [40]. This data is similar to that of the present investigation. In cadavers, gracilis, semitendinosus, and patella tendons, when warmed from room to body temperature showed similar increases in elasticity as shown here, but hamstring tendons showed more elasticity [39]. These findings on cadavers and rat tendons have supported the idea that a warm-up before exercise, especially in women, increases tendon elasticity [36]. In a recent review of over 10 000 female athletes, the data support a reduction in ACL tears with a warm-up [36].

Women are especially susceptible to ACL tears. This particularly occurs during the late luteal and early follicular phases, when body temperature is low [36]. The sports injury rate of women from ACL tears is reported as being about 3 times higher than in men, with an incidence rate 11 times higher in women engaged in military training than in men [5]. It would therefore appear that use of local heat, such as with a ThermaCare heat wrap, before athletic training and events, may be useful to include in a warm-up. The results of our study indicate that it increases elasticity and may help prevent injuries. The optimal time to apple local heat would be during mid-follicular phases of the menstrual cycle, since this is when body temperature is the lowest.

Changing the speed of movement of a limb during passive movement reveals properties of the elasticity of the tissues involved [41]. Concerning the passive stretching of the quadriceps muscle and its tendons by the CPM machine used here, previous experiments show that as the speed of movement increases, the series and parallel elastic components store more energy and therefore require more force [42]. Studies of the hysteresis of passive movement of the leg found that the mechanism of resistance is rearrangement of collagen, and is not due to fluid compartment changes [42]. EMG studies have shown that rapid movement does cause some reflex muscle activity. If, for faster rates of movement, any muscle activity was generated, then some of the resistance to movement may be related to energy stored in actin filaments during stretch. Actin is the main component of the thin filaments in muscle. During stretch and muscle contraction, the steep helical structure (70°) rotates and stores energy to aid the series elastic component in muscle [12]. This is due to the fact that the thin filaments are a double helix wound in a counterclockwise rotation [43]. During stretching, when there is active actomyosin bridge formation, they unwind and store elastic energy [43]. This may have added to the increased force required to flex the knee at high rates but at low rates of movement, probably due only to the elastic properties in the quadriceps muscle and its tendon [44,45]. These same 2 studies also suggest that the most accurate way to measure the passive elastic properties of tissue is slow movement, because rapid movement stores more elastic energy [42]. The data presented here are in agreement. Therefore, after the Group 1 experiment, only the lowest movement rate was used to study the effect of temperature on force needed to flex the knee. The increased force with cold and reduced force with heat are therefore probably attributed to the effect of heat and cold and the relaxation of collagen in the connective tissue in the quadriceps muscle and its tendons at higher temperatures. Adding to that is the data on the hysteresis between the flexion and extension forces. Here, there was a difference in the Group 2 subjects – 18.4 newtons at 20° flexion at the knee after the cold packs and 8.9 after heat packs – showing the difference in stored energy with cold compared to heat causing the passive properties of the muscle to be stiffer.

Conclusions

1. Cold increases the force necessary to passively move the knee through range of motion, whereas heat has the opposite effect.
2. Cold and heat alter both the elasticity of the anterior and posterior cruciate ligaments, as well as tendon and muscle.
3. There was more laxity in the anterior and posterior cruciate ligaments in women, but heat had the same relative beneficial effect.
4. Women showed more knee ligament laxness than men at all temperatures examined.

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