Passive energy absorption by human muscle-tendon unit is unaffected by increase in intramuscular temperature

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Magnusson, S. P., P. Aagaard, B. Larsson, and M. Kjaer. Passive energy absorption by human muscle-tendon unit is unaffected by increase in intramuscular temperature. J Appl Physiol 88: 1215–1220, 2000.—The present study measured hamstring intramuscular temperature and muscle-tendon unit viscoelastic properties in healthy young men before and after 10 and 30 min of running with (day S) or without stretch (day NS). On day S, passive energy absorption and intramuscular temperature were measured before running (Preex), after 10 min of running at 70% of maximum O₂ uptake (Postex10), and after 30 min of running at 75% of maximum O₂ uptake (Postex30). On day S, the protocol was repeated with three stretches (stretches 1–3) added after Postex10. Intramuscular temperature was elevated Postex10 (P < 0.01) and further Postex30 (P < 0.05). On day NS, the total energy absorbed Preex (14.3 ± 2.3 J), Postex10 (14.5 ± 3.2 J), and Postex30 (13.5 ± 2.4 J) was not different. On day S, the total energy absorbed in stretch 3 (10.8 ± 1.8 J) was lower than that Preex (14.5 ± 1.7 J, P < 0.01) and Postex10 (13.5 ± 1.9 J, P < 0.05) but not Postex30 (13.3 ± 1.8 J). The total energy absorbed Postex30 did not differ from Preex. In conclusion, warm-up and continuous running elevated intramuscular temperature but did not affect the passive energy absorption. Repeated passive stretching reduced the energy absorption immediately; however, the effect did not remain after 30 min of running. These data suggest that passive energy absorption of the human skeletal muscle is insensitive to physiological increases in intramuscular temperature.

viscoelastic behavior; static stretch; elasticity; extensibility

WARMING UP BEFORE SPORTS participation is commonly believed to aid performance and reduce injury risk (24). Furthermore, because the muscle-tendon unit is thought to exhibit temperature-dependent viscoelastic behavior, it is recommended that warm-up precede stretching exercises to enhance tissue extensibility (4, 8, 29). However, there is limited scientific evidence for such tenets.

The passive behavior of the muscle-tendon unit during stretch is a combination of viscous rate-dependent properties and elastic load-dependent properties. The tensile loading of the muscle-tendon unit during passive static stretching can be described in biomechanical terms: the loading is performed by stretching the target muscle to a new length (dynamic phase) where it remains for some time (static phase) before it is returned to the starting position (1, 24, 28, 33). In addition to strain-rate dependency, the viscous properties of biological tissue also depend on tissue history, temperature, and pressure (5).

The viscosity of a tissue diminishes with elevated temperature (21, 34, 37). It has been shown that the viscoelastic properties of animal tendon (14, 35), ligament (37), and muscle-tendon unit (1, 26, 31) will change with elevated temperature. However, with one exception (31), the temperature-dependent changes in viscous behavior have been conducted at temperatures other than the physiological range associated with warm-up procedures (3, 23, 27). Our laboratory has previously shown that the muscle-tendon unit in vivo displays viscoelastic properties during passive stretch but that the energy loss is rapidly recovered (18). However, to our knowledge, the effect of a warm-up procedure on the viscoelastic properties of human skeletal muscle remains unknown.

Several studies in humans have shown that maximal joint range of motion increases after a period of warm-up (11, 30, 32, 36). Although passive tissue properties have been shown to change with increased temperature in animal models, it remains to be established whether warm-up procedures and continuous exercise in a human model change the viscoelastic properties of the muscle-tendon unit. Therefore, the present study sought to examine whether the passive energy absorption of the muscle-tendon unit would decrease as a result of a brief (10-min) warm-up exercise bout and sustained (30-min) exercise with or without repeated stretches after the warm-up bout.

METHODS

Subjects

Eight male recreational-athlete volunteers gave written informed consent to participate in the study. The means ± SD for the age, body mass, and height were 30.5 ± 10.0 yr, 76.8 ± 7.6 kg, and 1.82 ± 0.04 m, respectively. The subjects were free of any lower extremity or low back pathology at the time of the study. All subjects exercised recreationally on a regular basis.

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basis. The study was approved by our institutional human subjects ethics committee.

Study Design

Measurements were obtained on 3 separate days. On the first day, the relationship between running velocity and oxygen uptake (V\(\dot{O}_2\)) was established. The 2 subsequent days were ordered randomly.

Day NS (no stretching). Resistance to stretch and intramuscular temperature was measured before (Preex) and after 10 min of running on the treadmill at a speed that corresponded to 70% of maximal V\(\dot{O}_2\) (V\(\dot{O}_2\)max), which constituted a “warm-up” period (Postex10). Immediately thereafter, the subjects ran for an additional 30 min on a treadmill at a speed that corresponded to 75% of V\(\dot{O}_2\)max, followed by additional measurements of resistance to stretch and intramuscular temperature (Postex30).

Day S (stretching). Resistance to stretch was measured before and after treadmill running in an identical fashion to that on day NS without, however, measuring intramuscular temperature. In addition, after 10 min of running, another three stretching (stretches 1–3) maneuvers were conducted.

Measurements

V\(\dot{O}_2\)max determination. To determine the relationship between running velocity and V\(\dot{O}_2\), a submaximal incremental test followed by a maximal test was performed on a treadmill. Three 5-min submaximal stages were performed with a 2 km/h speed increase for each stage. Initial running velocity was estimated according to running skill for each individual. After a 10-min rest period, the subjects performed a maximal test by running on 0% slope at a fixed speed for 2 min. Thereafter, the slope was raised 2% every 1.5 min to exhaustion. Cardiorespiratory metabolic variables were measured by using an AMIS 2001 automated metabolic cart (INNOVISION, Odense, Denmark). Mean V\(\dot{O}_2\), CO\(_2\) production, minute ventilation, and respiratory exchange ratio were calculated for each 15-s period. The mean of the two highest 15-s values was recorded as V\(\dot{O}_2\)max. The data were used to calculate the treadmill running velocity that corresponded to 70 and 75% of V\(\dot{O}_2\)max.

Passive properties. The measurement of passive muscle-tendon unit viscoelastic characteristics has been described in detailed elsewhere (16, 19). Briefly, resistance to stretch was defined as the passive moment of force (N·m) offered by the hamstring muscle group during a passive knee-extension maneuver with the use of an isokinetic dynamometer (Kinetic Communicator, Chattanooga, Chattanooga, TN) with a modified thigh pad. All measurements of passive moment were gravity corrected throughout the entire range of motion; the reference gravitational moment was obtained in the test position with knee flexed to 1.222 rad (70°) below horizontal (see below) (19). Subjects were seated with the trunk perpendicular to the seat for the stretch procedure. The thigh rested on a specially constructed thigh pad, which elevated it to 0.524–0.785 rad (range) from horizontal. The trunk and thigh position prevented subjects from reaching complete knee extension. Consequently, the position of the subject during the stretch maneuver placed tension primarily on the muscle-tendon unit without involvement of posterior capsular constraints about the knee. Passive force (N) was detected by the load cell of the dynamometer. The dynamometer and knee joint axis were aligned, and the moment about the knee joint was calculated by multiplying the measured force by the lever arm distance. Lever arm attachment was placed 2 cm proximal to the lateral malleolus. The subjects were positioned with the lower back and pelvis firmly against the back rest, and the distal thigh and pelvis were tightly secured with straps.

The stretch maneuvers (Preex, Postex10, Postex30, and stretches 1–3) were all administered to the left lower extremity of all subjects and consisted of a dynamic phase of slow passive knee extension to a predetermined final joint angle followed by a 90-s static phase (Fig. 1). The final joint angle during the stretch maneuver was determined for each individual. The subjects relaxed their muscles, and the investigator manually extended the knee to an angle that provoked a sensation of tightness in the posterior thigh, similar to a static stretch maneuver. Care was taken to avoid a painful response during determination of the final angle. The leg was
then immediately returned to the starting position. During the stretch maneuver, the dynamometer extended the knee passively at 0.087 rad/s (5°/s) from the starting point of 1.222 rad (70°) below horizontal to the final angle at which it remained for 90 s. Preex, Postex10, Postex30, and stretches 1–3 were all performed to the same predetermined individual final angle. The rest period between the three stretches was ~30 s. Subjects were requested to relax completely during the stretch maneuver so as not to offer any voluntary resistance.

Contractile activity. When passive resistance to stretch is measured in human skeletal muscle in vivo, the potential contribution of contractile activity needs to be accounted for. Using an identical measurement technique as in the present study, we have repeatedly demonstrated that there is no contractile activity of the hamstring muscle group that contributes to the resistance in the dynamic phase or subsequent viscoelastic stress relaxation during the static phase (17, 19, 20). Therefore, electromyographic (EMG) recordings were not the primary focus in this study. Nevertheless, EMG recordings [as previously described (19)] of the hamstring muscles were recorded in all subjects during all stretch maneuvers. The initial and final 1 s during the dynamic phase, and the initial and final 1 s of the static phase, yielding amplitudes of <10 µV (see Fig. 1). The EMG signal was recorded by using an amplification factor of 2,000 and subsequently converted back to its raw unamplified magnitude (µV). The low amplitudes are in accordance with previous data, which have demonstrated that the contractile component does not contribute to resistance to stretch in the dynamic or static phase of the stretch with the use of the present measuring setup (19, 20).

Temperature. Intramuscular temperature was measured with an accuracy of 0.1°C by using an intramuscular thermo-couple probe (DM 852, Ellab, Copenhagen, Denmark). The probe was inserted into the lateral aspect of the biceps femoris muscle, approximately midway between the ischial tuberosity and the medial knee-joint line. To avoid vessels and the thick iliotibial band laterally, the exact insertion site of the thermocouple probe was determined by use of ultrasound (Siemens Sonoline Versa Pro, Erlangen, Germany). After injection of a local anesthetic, the probe was inserted to a standardized subcutaneous depth of 20 mm, which, because of the low percent body fat of our subjects, corresponded to ~15 mm into the muscular portion of the biceps femoris. The probe was inserted in the same location for all three intramuscular readings (Preex, Postex10, and Postex30) on day NS.

Data Reduction and Analysis

Passive force, joint range of motion, angular velocity, and hamstring EMG were continuously recorded for all stretch maneuvers. Signals were sampled at 50 Hz, analog/digital converted, and stored on a personal computer for subsequent analysis. A fourth-order polynomial fit was applied to the moment-angle curves in the dynamic phase of the stretch maneuvers (5, 6, 19) (Fig. 2). By converting the angular change into radians, absorbed energy could be calculated as the area covered by the polynomial moment-angle curve in the entire range. For the static phase of the stretch maneuvers, peak moment was obtained the instant the lever arm reached the final angle, and decline in moment was expressed as a percentage of peak moment and was referred to as visco-elastic stress relaxation (see Fig. 1) (16, 18–20).

Separate nonparametric one-way ANOVAs (Friedman test) with Dunn’s multiple comparison post hoc tests were used to evaluate the effect on day NS (Preex, Postex10, and Postex30) and day S (Preex, Postex10, Postex30, and stretch 3). An alpha level of 0.05 was considered significant. Results are reported as means ± SE.

RESULTS

The treadmill test yielded a $\dot{V}O_{2\text{max}}$ of 63.3 ± 2.7 ml·kg$^{-1}$·min$^{-1}$ with a corresponding maximal heart rate of 188 ± 3 beats/min. The calculated running velocity at 70 and 75% corresponded to 13.0 ± 0.8 and 13.9 ± 0.8 km/h, respectively.

Hamstring intramuscular temperature was 35.0 ± 0.4°C Preex, 38.0 ± 0.2°C Postex10, and 38.8 ± 0.3°C Postex30. There was a significant effect of time (P < 0.001). Temperature was significantly elevated Postex10 (P < 0.01) and was further raised Postex30 (P < 0.05).

The average passive knee-joint extension was 73 ± 6° (i.e., 3° above horizontal). The passive energy absorption in the dynamic phase from day NS is shown in Fig. 3. The total absorbed energy Preex (14.3 ± 2.3 J), Postex10 (14.5 ± 3.2 J), and Postex30 (13.5 ± 2.4 J) was not significantly different. The passive energy absorption in the dynamic phase from day S is shown in Fig. 4. There was an overall effect of time (P < 0.01) such that the total energy in stretch 3 (10.8 ± 1.8 J) was lower than that Preex (14.5 ± 1.7 J) and Postex10 (13.5 ± 1.9 J) (P < 0.01) but not Postex30 (13.3 ± 1.8 J). The total energy absorbed Postex30 did not differ from Preex. In the static phase of all stretch maneuvers (stretches 1–3), a significant stress relaxation was observed (29 ± 1%, P < 0.001; see Fig. 1).

DISCUSSION

The main findings of the present study were that a 10-min warm-up procedure and 30 min of continuous running elevated intramuscular temperature significantly but did not measurably affect the passive energy absorption of the hamstring muscle-tendon unit. Fur-
therefore, although the intramuscular temperature elevation did not affect the viscoelastic properties, repeated passive stretching that resulted in 29% stress relaxation immediately reduced the passive energy absorption. However, this reduction in passive energy absorption was not sustained after an additional 30 min of continuous running.

Previous work on intramuscular temperature associated with lower extremity work has focused on the quadriceps muscle (12, 23, 27). The present study shows that running produces similar increases in intramuscular temperature in the hamstring muscle group. It has been shown that 60 min of ergometer bicycling at workloads corresponding to ~70% of $V_{O2max}$ increase intramuscular temperature in the quadriceps muscle from 36.5°C at rest to 39.2°C (27). Our data show that the biceps femoris muscle had a resting intramuscular temperature of 35.0°C. After 10 min of running at a speed that corresponded to 70% $V_{O2max}$, intramuscular temperature rose to 38.0°C, and an additional 30 min at 75% $V_{O2max}$ further increased the temperature to 38.8°C, demonstrating the heat production associated with muscular activation and exercise. It is well known that continuous exercise rapidly results in an equilibrium between heat production and heat dissipation. Although there was a significant intramuscular temperature elevation from 10 min of warm-up to 30 min of continuous exercise, it should be noted that ~80% of the temperature increase occurred in the initial 10 min of work. This confirms that increased tissue temperature can be achieved relatively soon after initiation of exercise and that 10 min of warm-up exercise may be sufficient preparation for muscle performance (3).

In animal models, it is well established that the viscoelastic behavior of tendon and the muscle-tendon unit is altered with increased tissue temperature such that stiffness decreases and length and force to failure increase (1, 14, 21, 26, 31, 34, 35, 37). However, it is noteworthy that these changes in viscoelastic behavior were observed over temperature ranges of 10–35°C (22), 25–45°C (14), 25–40°C (24), and 2–37°C (37). Whereas these studies all demonstrate temperature-dependent viscoelastic behavior of biological tissue, the temperature ranges far exceed those achieved during a warm-up procedure in human skeletal muscle (3, 23, 27). In contrast, Strickler et al. (31) examined biomechanical responses of the rabbit tibialis anterior and extensor digitorum longus muscle-tendon unit at temperatures of 35 and 39°C. The passively heated muscle-tendon units yielded at a greater length and failed at a lower force. Theoretically, decreased force and increased length to failure would result in reduced energy absorption for a given length change. The present protocol yielded temperature elevations similar to that of Strickler et al. However, in contrast, our data show that the energy absorption of the human skeletal muscle at a fixed length change remains unchanged despite the elevated intramuscular temperature. Furthermore, it should be noted that previous animal models have used passive modes of heating. However, it is known that repeated mechanical loading will shift the length-tension curve of the muscle-tendon unit to the right (34), which results in reduced energy absorption for a given length change. In the present study, treadmill running, i.e., repeated mechanical loading, was used to elevate tissue temperature. Despite the repeated mechanical loading during 40 min of running and its associated increase in intramuscular temperature, the passive energy absorption was unchanged. It has been suggested that elastic recoil may play a role in energy expenditure during locomotion (2, 9, 25), and, albeit speculative, the temperature and
repetitive load-insensitive passive energy behavior may serve to maintain passive elastic energy return during locomotion.

Stretching exercises are believed to alter the viscoelastic behavior of the muscle-tendon unit and thereby reduce muscle-tendon injury risk (8). Therefore, because elevated temperature has been shown to increase muscle-tendon extensibility to achieve optimal effect, it is commonly recommended that a warm-up procedure precede any stretching regimen (8, 29). The present study showed that passive energy absorption remained unchanged with a warm-up procedure consisting of 10 min of running at 70% of $V_{\text{O}_2\text{max}}$. After the warm-up, four repeated static stretch maneuvers of 90 s significantly reduced the passive energy absorption by ~25%, which is in accordance with previous data that show that muscle at resting temperature will reduce passive energy absorption by ~30% with five repeated 90-s static stretch maneuvers (18). Moreover, it was recently observed that three repeated 45-s static stretches did not alter the passive energy absorption, despite a 20% viscoelastic stress relaxation in each stretch maneuver (15). However, in the present study, the repeated static stretches reduced passive energy absorption, although the effect was not sustained after 30 min of treadmill running at 75% of $V_{\text{O}_2\text{max}}$. Therefore, together, these observations on the viscoelastic properties of the human hamstring muscle group suggest that the time of static loading has a greater influence on the energy absorption than does any temperature increase associated with muscle work. Furthermore, the observations suggest that any decline in energy absorption from stretching is rapidly reversed, and its potential effect in altering muscle-tendon unit failure properties may therefore be questioned.

It should be noted that the present study measured intramuscular temperature, and no attempts were made to monitor tendon temperature. It has recently been demonstrated that blood flow in the peritendinous space of the human Achilles tendon can be elevated fourfold during 40 min of dynamic contractions of triceps surae muscle (13), suggesting that tendon blood flow and temperature are likely elevated with exercise. In the present study, exercise did not significantly change passive energy absorption of the muscle-tendon unit, and, therefore, it is unlikely that the tendon properties were significantly changed as a result of the exercise.

It has been established that muscular work during a warm-up procedure results in improved maximal joint range of motion, which has been interpreted as an increased muscle-tendon extensibility (11, 30, 32, 36). However, the present data demonstrate that a warm-up procedure that produces a marked increase in intramuscular temperature does not alter the passive energy absorption for a given length change. Although not investigated in the present study, it is possible that improved flexibility associated with warm-up is a change in the tolerance to the imposed tensile loading. It has previously been shown that chronic stretching and muscle contraction may alter tolerance to tensile loadings (17, 19). Therefore, warm-up-associated improvements in flexibility may be the result of an altered tolerance from the increased tissue temperature, repetitive mechanical loading (17, 19), or plasma beta-endorphin levels (7).

In accordance with previous observation (18), the present study demonstrated that prolonged repeated static stretch has an immediate effect on passive energy absorption, although the effect disappeared during the subsequent 30-min treadmill running. Although the present data failed to show that the repeated loading of the muscle-tendon unit and the elevated intramuscular temperature significantly affected passive resistance to stretch, it should be kept in mind that the sample size was rather small ($n = 8$). Therefore, it is appropriate to address the issue of statistical power of the study or the ability to avoid a type II error (10).

In summary, the present study investigated whether passive energy absorption in the human hamstring muscle group in vivo was affected by a warm-up procedure, sustained exercise, and stretching exercises after a warm-up procedure. The data showed that a 10-min warm-up procedure followed by 30 min of continuous running, which both produced significant intramuscular temperature elevation, did not measurably affect the passive energy absorption of the hamstring muscle-tendon unit for a given length change. Furthermore, whereas muscular and increased tissue temperature did not appreciably affect the viscoelastic properties, repeated passive loading that resulted in 29% stress relaxation immediately reduced the passive energy absorption. However, the reduction in energy absorption was short lasting and was not sustained after 30 min of continuous running. These data suggest the possibility that passive energy absorption of the human skeletal muscle is insensitive to increases in intramuscular temperature in a physiological range.

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