Effects of Warm-up on Peak Torque, Rate of Torque Development, and Electromyographic and Mechanomyographic Signals

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Abstract

Altamirano, KM, Coburn, JW, Brown, LE, and Judelson, DA. Effects of warm-up on peak torque, rate of torque development, and electromyographic and mechanomyographic signals. J Strength Cond Res 26(5): 1296–1301, 2012—The purpose of this study was to determine if an active warm-up affects peak torque (PT), rate of torque development (RTD), and the electromyographic (EMG) and mechanomyographic (MMG) signals. Twenty-one men (mean age ± SD: 24.0 ± 2.7 years) visited the exercise physiology laboratory on 2 occasions. During the first visit, they either performed an active warm-up (10 minutes of stationary cycling at 70% of predicted maximum heart rate) or sat quietly (no warm-up). Participants were then tested for isometric and isokinetic (60°, 180°, and 300°·s⁻¹) PT, and RTD (measured as S-gradient) on an isokinetic dynamometer. Electromyographic and MMG sensors were placed over the vastus lateralis muscle to monitor the electrical and mechanical aspects of muscle contractions, respectively. The testing protocol used for the first visit was repeated for the second visit, but the preexercise treatment (warm-up, no warm-up) not given during the first visit was administered. The results indicated that an active warm-up did not affect PT, RTD, or measures of muscle activation as reflected by EMG amplitude, EMG frequency, or MMG frequency (p > 0.05). However, MMG amplitude at 180°·s⁻¹ was significantly greater in the warm-up condition compared with the no warm-up condition. The isolated increase in MMG amplitude suggested that warm-up may have affected the mechanical properties of muscle by reducing muscular stiffness or decreasing intramuscular fluid pressure, but that it was not sufficient to influence performance.

Key Words muscular strength, isokinetic, isometric, power, EMG, MMG

Introduction

Strength and power are recognized as essential components of physical fitness and as primary contributors to sport performance. Theoretically, strength and power performance may be affected if they are preceded by a warm-up. Most studies that have investigated the effects of warm-up have examined physiological changes (15,16,23). Fewer studies have investigated warm-up effects on performance measures, such as muscular strength and power. The limited warm-up research that has examined strength has primarily tested isometric strength and has reported little or no significant effects on performance (2,5–8,12). The limited research that has examined dynamic muscle actions after active warm-up has suggested that there may be beneficial effects on muscular performance measures (7,20). For example, although isometric knee extension strength was unaffected by an active warm-up, there was a significant increase in instantaneous squat jump power after a warm-up compared with a no warm-up control condition (20). Bergh and Ekblom (5) found significant elevations in peak torque (PT) and maximal power after active warm-up when compared with control and cold trials. Others have reported decreased time to peak tension and half-relaxation time, but no change in isometric strength (12).

It is reasonable to conclude that warm-up might affect rate of force or rate of torque development (RTD) and dynamic strength more than isometric strength, particularly at higher muscle-shortening velocities (7). For example, warming may reduce the viscous resistance of muscles and joints (24,25), increase nerve conduction velocity (14), and reduce the passive stiffness of muscle (22). Theoretically, each of these changes should enhance performance when maximal RTD and power are desired (7).

Stewart et al. (20) used electromyography (EMG) to aid in explaining the physiology behind the squat jump performance increase. They concluded that the significant increase in instantaneous power during the squat jump after warm-up may have been partially because of an increase in action potential conduction velocity, as evidenced by an increase in the median frequency of the EMG signal. Because the amplitude of the EMG signal is related to motor unit...
activation (recruitment and firing rate) and the frequency is related to the average action potential conduction velocity of the active motor units (9), EMG has proven useful in studying neuromuscular physiology. Mechanomyography (MMG) measures the low-frequency sounds produced by contracting skeletal muscle. These sounds are believed to result from (a) a gross lateral movement of the muscle at the initiation of contraction, (b) smaller subsequent lateral oscillations that occur at the resonant frequency of the muscle, and (c) dimensional changes of the active muscle fibers (3). It has been suggested that the amplitude of the MMG signal is related to motor unit activation, whereas the frequency of the MMG signal may be related to the firing rate of the active motor units (4,17). Simultaneous use of EMG and MMG may provide useful information regarding electrical and mechanical changes to muscle function after warm-up.

Although some studies have examined the effects of warm-up on both isometric and dynamic performance measures, to our knowledge, none have compared responses during identical movements (i.e., leg extensions done at various angular velocities) or using methodologies that allow for comparison of electrical (EMG) and mechanical (MMG) changes resulting from warm-up. In addition, most studies have used warm-up protocols that are dissimilar to those prescribed for use in practical settings. Therefore, the purpose of this study was to examine the effects of warm-up on isometric and isokinetic leg extension strength, RTD, and the amplitude and frequency of EMG and MMG signals, using a warm-up protocol that is more typical of those used by strength and conditioning practitioners.

**METHODS**

**Experimental Approach to the Problem**

A randomized (first subject), then balanced, crossover design was used. Participants were tested for leg extension isometric strength, isokinetic PT at 60°, 180°, and 300° s⁻¹, and RTD on a HUMAC NORM Testing and Rehabilitation system (CSMi, Inc., Stoughton, MA, USA). Electromyographic and MMG sensors were placed over the vastus lateralis muscle of the right limb to monitor the electrical and mechanical aspects of muscle actions, respectively. To our knowledge, this is the first study to directly compare warm-up effects on a single exercise (leg extension), performed at variable angular velocities. In addition, we are unaware of previous research that has examined the effects of warm-up on RTD, while simultaneously recording both EMG and MMG signals.

**Subjects**

Twenty-one men volunteered to participate in each of the 2 trials (control and active warm-up). The subjects were primarily kinesiology students with moderate to high-resistance training experience. The mean age, height, and mass of the subjects were 24.0 ± 2.7 years, 176.7 ± 6.6 cm, and 87.0 ± 17.1 kg, respectively. This study required 2 visits, lasting approximately 1 hour per visit. All subjects signed an informed consent form prior to participating in the study, and the study was approved by the Institutional Review Board.

**Procedures**

Each participant visited the laboratory on 2 occasions. During each visit, room temperature and humidity were recorded (22.97 ± 0.15°C and 32.00 ± 4.45%). Hydration status was controlled for by instructing each subject to consume 1 L of water above normal consumption the evening before the trial and ½ L of water in the morning of the trial. Subjects were scheduled at the same time of day for each trial and instructed to avoid resistance training of the leg musculature during the duration of the study. Each subject’s isometric and isokinetic strengths were determined during each visit. Height and body mass were measured and recorded. Electromyographic and MMG sensors were placed on the skin after the treatment (control or active warm-up) had been administered and before the subject performed isometric and isokinetic strength testing. The order of trials (control or active warm-up) was randomized and balanced between subjects. There was a minimum of 48 hours between trials.

**Active Warm-up Protocol**

Each subject cycled at 70% of their age-predicted maximum heart rate (220 minus age) ÷ 4 b-min⁻¹, for 10 minutes on a cycle ergometer (Monark 839E). Heart rate was used to gauge warm-up intensity, rather than a percentage of Vo₂max or core or muscle temperature, because it is a practical measure that is easy to calculate and is frequently prescribed for use in applied settings. The specific intensity was chosen because it corresponds to warm-up intensities that have been suggested to enhance performance (1), including anaerobic exercise performance (21). To determine the correct exercise intensity for this warm-up, each subject began pedaling at 80 W and the power output was then increased by 30 W every 2 minutes until the target heart rate was attained. Each subject then continued to warm-up at this power level for 10 minutes. Heart rate was monitored continuously each minute until the end of the warm-up using a Polar heart rate monitor (Polar Electro, Inc., Lake Success, NY, USA). When necessary, the power level was adjusted up or down to stay within the prescribed heart rate range. Immediately upon completing the active warm-up, EMG and MMG sensors were attached and strength testing began.

**Control Protocol**

Strength testing during the control visit was identical to that of the active warm-up visit except that subjects sat motionless for 20 minutes (the approximate time for warm-up and strength test preparation) rather than performing the warm-up protocol.

**Isometric and Isokinetic Strength Testing and Rate of Torque Development**

Maximal isometric and isokinetic strength of the right leg extensors were measured using a calibrated HUMAC NORM
The subjects were seated according to the HUMAC NORM Testing and Rehabilitation system user’s guide. Isometric strength was determined with the lever arm of the dynamometer placed at an angle of 0.785 rad (45°) below the horizontal plane. Two maximal 6-second isometric muscle actions were performed, with the highest value selected as the maximal isometric strength value. The subjects then performed 3 maximal, concentric isokinetic muscle actions of the leg extensors of the right limb at each of 3 velocities (60°/s, 180°/s, and 300°/s) for the determination of PT. The highest value from the 3 muscle actions was considered the PT. A 2-minute rest period was allowed between each velocity. The subjects were verbally encouraged to produce as much torque as possible. Rate of torque development was determined from the contraction associated with the maximal isometric strength value (measured as S-gradient; $S_{\text{gradient}} = F_{0.5}/T_{0.5}$, where $F_{0.5}$ is one half of the maximal force and $T_{0.5}$ is the time to attain it (26)). The intraclass reliability coefficient for strength measurements was $R = 0.96$.

### Electromyographic and Mechanomyographic Measurements and Signal Processing

A bipolar (5.4 cm center-to-center) surface electrode (EL500 silver-silver chloride; BIOPAC Systems, Inc., Santa Barbara, CA, USA) arrangement was placed over the longitudinal axis of the vastus lateralis muscle of the right limb. The interelectrode distance was selected to accommodate placing the MMG sensor between the EMG electrodes. The electrode placement for the vastus lateralis was 2/3 on the line from the anterior spina iliaca superior to the lateral side of the patella. The reference electrode was placed over the iliac crest. Interelectrode impedance was kept below 2,000 Ω by shaving the area and careful skin abrasion. The EMG signal was preamplified (gain ×1000) using a differential amplifier (EMG 100C; BIOPAC Systems; bandwidth = 1–500 Hz). The MMG signal was detected by an

### Table 1. Normalized isokinetic peak torque values (mean ± SD) for the warm-up and no warm-up conditions.*

<table>
<thead>
<tr>
<th>Velocity</th>
<th>Warm-up</th>
<th>No warm-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>60°/s⁻¹</td>
<td>0.89 ± 0.12</td>
<td>0.96 ± 0.16</td>
</tr>
<tr>
<td>180°/s⁻¹</td>
<td>0.59 ± 0.09</td>
<td>0.57 ± 0.10</td>
</tr>
<tr>
<td>300°/s⁻¹</td>
<td>0.51 ± 0.08</td>
<td>0.51 ± 0.07</td>
</tr>
</tbody>
</table>

*Peak torque values were normalized to the highest maximal voluntary isometric contraction value measured during the no warm-up condition. There were no significant ($p \geq 0.05$) differences in normalized peak torque between conditions. There was a significant main effect for velocity (60 > 180 > 300°/s⁻¹).

### Table 2. Normalized electromyographic and mechanomyographic amplitude (root mean square) and frequency (mean power frequency) values (mean ± SD) for the warm-up and no warm-up conditions.*

<table>
<thead>
<tr>
<th>Velocity</th>
<th>EMG amplitude</th>
<th>EMG MPF</th>
<th>MMG amplitude</th>
<th>MMG MPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>60°/s⁻¹</td>
<td>1.02 ± 0.33</td>
<td>0.97 ± 0.35</td>
<td>1.06 ± 0.14</td>
<td>1.76 ± 0.66</td>
</tr>
<tr>
<td>180°/s⁻¹</td>
<td>0.98 ± 0.35</td>
<td>1.01 ± 0.37</td>
<td>0.97 ± 0.20</td>
<td>2.00 ± 1.68</td>
</tr>
<tr>
<td>300°/s⁻¹</td>
<td>1.05 ± 0.36</td>
<td>1.07 ± 0.17</td>
<td>1.07 ± 0.17</td>
<td>1.94 ± 0.93</td>
</tr>
</tbody>
</table>

*Electromyographic and mechanomyographic root mean square and mean power frequency values were normalized to the highest maximal voluntary isometric contraction value measured during the no warm-up condition. There was no significant ($p \geq 0.05$) interaction or main effects for condition or velocity with the exception that the normalized MMG root mean square value at 180°/s⁻¹ was significantly ($p < 0.05$) greater for the warm-up condition. EMG = electromyographic; MMG = mechanomyographic; MPF = mean power frequency.

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accelerometer (EGAS-FT-10−/V05, Entran, Hampton, VA, USA). The accelerometer was placed over the vastus lateralis muscle between the 2 EMG electrodes. Double-sided foam tape and microporous tape were used to ensure consistent contact pressure of the accelerometer.

The raw EMG and MMG signals were stored and displayed on a personal computer using data acquisition software (AcqKnowledge 3.8.1; BIOPAC Systems). The sampling frequency was 1,000 Hz for both signals. The EMG and MMG signals were bandpass filtered (fourth-order Butterworth filter) at 10–500 and 5–100 Hz, respectively. The middle 2 seconds of the 6-second isometric muscle actions were used for analyses. The EMG and MMG amplitude and frequency values for the isokinetic muscle actions were calculated for a time period that corresponded to a 50° range of motion from approximately 110° to 160° of leg flexion (i.e., at 60°·s⁻¹ the amplitudes and frequencies for 0.83 seconds of the MMG and EMG signals were calculated, at 180°·s⁻¹ the amplitudes and frequencies for 0.28 seconds were calculated, and at 300°·s⁻¹ the amplitude and frequencies for 0.17 seconds were calculated). The amplitudes were expressed as root mean square amplitude values. All frequency analyses were performed with custom programs written with LabVIEW software (version 7.1; National Instruments, Austin, TX, USA). Frequency data were expressed as mean power frequency (MPF). Each MMG data segment was processed with a Hamming window and discrete Fourier transformation.

### Results

The results of the study indicated that there was no significant 2-way interaction for PT and warm-up condition (Table 1). However, the PT data did demonstrate a significant main effect for velocity (60 > 180 > 300°·s⁻¹). There were no significant 2-way interactions or main effects for normalized EMG amplitude, EMG frequency, or MMG frequency (Table 2). There was, however, a significant 2-way interaction for MMG amplitude (Table 2). Follow-up tests revealed that MMG amplitude at 180°·s⁻¹ was significantly greater in the warm-up condition compared with the no warm-up condition. The results of the analyses indicated that there was no significant difference in isometric strength (Table 3) or RTD (Figure 1) between the warm-up and no warm-up conditions.

### Discussion

The purpose of this investigation was to examine whether an active warm-up, as typically prescribed for use in practical settings, affected muscular performance. The results indicated that warm-up did not affect isometric or isokinetic strength, or RTD. Previous research suggested that dynamic movements could be positively affected by changes in temperature (5). For example, it has been proposed that increased muscular temperature may increase action potential conduction velocity and the rate and synchronization of crossbridge cycling, thereby increasing dynamic, but not isometric, strength (5,20). The isometric strength results of the current study are consistent with this theory and with previous research (7,12,19,20), as warm-up did not affect isometric strength.

The dynamic strength results of the present study differ from previous research (5,20). For example, significant increases in isokinetic PT have been described when leg extensions were preceded by an active warm-up (5). In the present study, the dynamic warm-up did not affect PT at
any velocity during the isokinetic leg extensions. The differences between the present study and others (5) may be because of the variability in the degree of temperature increases and variety of warm-up and testing protocols. For example, other studies (5) varied the volume and intensity of warm-up exercise to elicit desired changes in muscle and esophageal temperatures. The purpose of the present study, however, was to prescribe a specific level of warm-up that is commonly prescribed for use in “real-world” settings and to see if it affected performance measures. Muscle temperature was not measured in the present study, so there is no way to know the change in muscular temperature that occurred from participation in the active warm-up protocol used. However, it is reasonable to conclude that the typical warm-up protocol recommended by prominent professional organizations (1) may not be sufficient to increase dynamic strength.

In the present study, RTD was not affected by warm-up. This is in agreement with previous research (10). For example, no significant change in RTD or muscular force was found after immersion in a 40°C water bath (10). Once again, the results for RTD suggest that the warm-up protocol in the present study was insufficient to affect dynamic muscle performance.

Electromyography is used to measure the electrical activity associated with muscle actions. Electromyographic amplitude assesses activation by measuring motor unit recruitment and firing rates. It is believed that action potential conduction velocity is associated with EMG frequency. The present study found no change in the amplitude or frequency of the EMG signal after warm-up. This suggests that warm-up, as used in this study, does not affect muscle activation or electrical properties. This is consistent with the findings of others who found no change EMG amplitude or frequency (5). Others, however, found decreased EMG amplitude and increased EMG frequency when a maximal voluntary isometric contraction was preceded by a warm-up (20). The increased EMG frequency was attributed to the “warm-up effect” and it was suggested that this reflected an increased action potential conduction velocity along the sarcolemma. Once again, the differing results between studies may have been because of differences in the magnitude of change in muscular temperature resulting from different warm-up protocols.

Mechanomyography is a measure of muscle vibration. It is typically used to examine mechanical processes of muscle actions. Mechanomyographic amplitude reflects motor unit recruitment, whereas MMG frequency reflects motor unit firing rates (4,9). The MMG signal is also influenced by intramuscular fluid pressure, muscular stiffness, and crossbridge cycling (11,18), and skin temperature (15), all properties that may be influenced by warm-up. Consistent with previous studies (13), we found no change in MMG frequency between trials or across velocities, suggesting that neither warm-up nor increased testing velocity affected the firing rates of the active motor units. In addition, there were no changes in MMG amplitude at 0, 60, or 300°·s⁻¹. However, MMG amplitude was significantly greater in the warm-up condition at 180°·s⁻¹. The increased MMG amplitude at 180°·s⁻¹ does not likely indicate increased motor unit recruitment because there were no changes in EMG amplitude or PT. More likely, the isolated finding of this increase in MMG amplitude reflects decreased muscular stiffness and intramuscular fluid pressure (7). This may be physiologically significant because it shows that warm-up does have a mechanical effect on muscle.

In conclusion, active warm-up as used in the present study had no effect on muscular performance or electrical activity. However, mechanical changes, as reflected by an increase in MMG amplitude, did occur at 180°·s⁻¹. Further studies are necessary to investigate the effects of different intensities and durations of active warm-up on isometric and dynamic muscle performance. Additionally, the results suggested that the use of EMG and MMG was beneficial for examining the differential effects of warm-up on the electrical and mechanical properties of muscle, respectively.

**Practical Applications**

Warm-up as used in the present study did not affect isometric or dynamic strength or RTD. These results suggest that protocols commonly recommended consisting of 10 to 20 minutes of warm-up and stretching to reduce injury risk and enhance performance may not be sufficient to achieve the latter. Future research should examine different intensities and durations of warm-up to determine the optimum protocol to use, if any, to enhance performance.

**References**


