Contents

Abstract

Purpose: The aim of this experiment was to investigate if a warm-up period prior to eccentric exercise has a preventive effect on the increased sensitivity to pain, and the loss of force, associated with delayed onset muscle soreness (DOMS). **Methods:** Twenty-four subjects were randomly assigned into a warm-up group (N=12) or a control group (N=12). The warm-up group completed 20 minutes of ergometer cycling, with an intensity of 60-70 % of estimated maximal heart rate, prior to eccentric exercise, while the control group did not perform warm-up prior to the eccentric exercise. DOMS was induced by completing 5 sets of 10 forward lunges (eccentric exercise). The outcome measures were: subjective evaluation of pain on a 100 mm. visual analogue scale (VAS), a pressure-pain threshold (PPT) on various locations of the m. rectus femoris, and isometric maximal voluntary contraction force (MVC), collected prior to exercise, 24-and 48 hours following exercise. **Results:** Both groups had significantly lower PPT in the distal region of the m. rectus femoris 24 hours following eccentric exercise. However, only the control group had a significant decrease in PPT in the proximal region of the m. rectus femoris. In addition, the warm-up group developed significantly less pain than the control group in the proximal region of the m. rectus femoris between baseline and 24 hours following exercise. Both groups had a significant decrease in MVC, and more pain (VAS) following exercise. Moreover, there were no significant differences between groups in MVC and VAS 24 and 48 hours following exercise. **Conclusion:** Our results suggest that warm-up prior to eccentric exercise might have a preventive effect on DOMS measured as the pressure pain threshold. The preventive effect seems to be most prominent in the proximal region of the muscle 24 hours following exercise.

Key words: Warm-up, delayed onset muscle soreness, DOMS, eccentric exercise, pressure-pain threshold, PPT, visual analogue scale, VAS, maximal voluntary contraction force

1. Introduction

Most people have experienced pain and discomfort the first few days following a training session. This pain might impair physical performance and complicate everyday activities. This harmful experience can be referred to as delayed onset muscle soreness (DOMS). DOMS often occurs following severe eccentric exercise that the practitioner is unaccustomed to (Proske and Morgan, 2001; Byrnes et al., 1985). It is classified as a light muscle strain injury (Safran et al., 1989), associated with pain in the affected muscles during movement (Jönhagen et al., 2009; Nosaka et al., 2004) or palpation (Nosaka et al., 2004; Nosaka et al., 2002), and a decrease in the range of motion (Chen et al., 2009; Gulick et al., 1996) and in maximal strength (Evans et al., 2002; Cleak and Eston, 1992). The pain sensation occurs 8 hours following the exercise (Newham et al., 1983) and peaks at 24 – 72 hours following the exercise (Nosaka et al., 2002; Rodenburg et al., 1994; Cleak and Eston, 1992). It is generally agreed on that eccentric exercise leads to muscle damage due to overstretched muscle fibers (Lauritzen et al., 2009; McNeil and Khakee, 1992; Fridén et al., 1983; Fridén et al., 1981). This damage is assumed to cause a series of events, which eventually result in inflammation and DOMS (Howatson and Someren 2008; Cheung et al., 2003; Connolly et al., 2003; Proske and Morgan 2001). However, the exact series of the events remain uncertain.

Quantifying the pain that follows eccentric exercise can be a challenge. Since pain is based on subjective experience, it is difficult to quantify (Revill et al., 1976; Ohnhaus and Adler, 1975). The visual analogue scale (VAS) is one of the most commonly used tools to measure the magnitude of pain associated with DOMS (e.g. Nosaka and Clarkson, 1997; Gulick et al., 1996). In recent years, quantifying DOMS with algometers measuring pressure-pain threshold (PPT) has become more common (e.g. Hedayatpour et al., 2008; Dannecker et al., 2002). Both VAS (Price et al., 1983) and algometers (Kinser et al., 2009; Ylinen et al., 2007) are reported to be valid and reliable. Maximal voluntary contraction force is also commonly measured in experiments regarding DOMS (e.g. Nosaka and Clarkson, 1997; Rodenburg et al., 1994). The magnitude of force loss following eccentric exercise has been claimed to be the best indirect marker of muscle damage (Warren et al., 1999). However, indirect markers cannot be used as evidence for muscle damage (Fridén and Lieber, 2001).

Many different treatment strategies for DOMS have been proposed. Strategies such as cryotheraphy, stretching, massage and compression seems to have no or limited effect with respect to the treatment of DOMS (Howatson and Someren, 2008; Cheung et al., 2003; Connolly et al., 2003). The use of anti inflammatory or nutritional treatment has shown inconclusive results, but there seems to be some evidence that NSAIDS, vitamin C and vitamin E can contribute in shortening the period of soreness resulting from eccentric exercise (Howatson and Someren, 2008; Cheung et al., 2003; Connolly et al., 2003). Exercise has been suggested as both a treatment strategy, and as a prevention modality of DOMS. Active recovery has shown to have a positive effect on removal of toxic waste products (Dodd et al., 1984), and is supposed to act as an analgesic effect in the first few hours following exercise (Koltyn, 2000). However, active recovery does not seem to have a treating effect on DOMS (Gulick et al., 1996; Law and Herbert, 2007). Warm-up exercises prior to demanding physical activity is thought to be an effective modality to prevent muscle injuries. However, there is limited scientific evidence supporting this (Woods et al., 2007; Bishop, 2003). Previous experiments have shown inconclusive results regarding the effect of warm-up on DOMS. Some experiments have found a preventive effect (Law and Herbert, 2007; Nosaka and Clarkson, 1997) while others have not (Evans et al., 2002; High et al., 1989). Although a preventive effect on DOMS was found by Rodenburg and co-workers (1994), their experiment combined several treatment strategies (warm-up, stretching and massage), thus it cannot be concluded that the warm-up provided the preventive effect.

Several beneficial effects of warm-up prior to exercise have been proposed. It has been suggested that warm-up leads to: increased energy supply to the muscles (Febbraio et al., 1996; Edwards et al., 1972), increased transmission rate of the nerve impulses (Bishop, 2003), reduced internal viscosity which results in smoother contractions (Safran et al., 1988), increased muscle activation and thus force (Girard et al., 2009; Skof and Strojnik, 2007) and increased blood and oxygen supply to the working muscle (Woods et al., 2007). However, it is unknown if any of these potentially beneficial effects of warm-up can reduce muscle damage and/or prevent DOMS.

Elevating muscle temperature by warming up has been suggested as a modality to prevent DOMS (Law and Herbert, 2007; Evans et al., 2002). This suggestion is based on the assumption that: Warm-up speeds up the metabolic processes in the active muscle and elevates the muscle temperature (Safran et al., 1989). Studies have shown that an elevation of muscle temperature increases muscle extensibility (Noonan et al., 1993; Strickler al., 1990). The increased muscle extensibility is expected to reduce the chance of muscle injury resulting from overstretched muscles (Safran et al., 1988; Shellock and Prentice, 1985). Thus, it seems plausible that literally warming up the muscles prior to eccentric exercise would lead to less muscle damage resulting from overstretched muscle fibers, and possibly result in less DOMS.

Further on, it seems to be a close relationship between the severity of the warm-up and the increase in muscle temperature. Saltin and co-workers (1968) showed that muscle temperature had a fast increase the first 5 minutes of exercise, and peaked after 10-20 minutes. They also showed that muscle temperature elevates more when the intensity of the exercise is increased (Saltin et al., 1968). Most experiments investigating the effect of warm-up on DOMS have used warm-up interventions with only light or moderate intensity and with a duration of only 3-10 minutes.

We hypothesized that a prolonged warm-up period with relatively high intensity would elevate muscle temperature, and thus prevent some of the harmful effects associated with DOMS. Therefore, the aim of the experiment was to investigate the effect of 20 minute warm-up (60-70 % of estimated maximal heart rate) prior to unaccustomed eccentric exercise, with regard to the increased sensitivity to pain and the loss of force associated with DOMS.

2. Materials and methods

This thesis is based on parts of the data derived from a larger randomized controlled trial concerning the effect of warm-up versus cool-down on the development of DOMS. The randomized control trial study design is frequently used in studies where the objective is to evaluate the effect of a treatment compared to no treatment. Subjects were randomly assigned to a warm-up (N=12), cool-down (N=12) or control group (N=12). This paper will only focus on the effect of warm-up on the development of DOMS. The data from the cool-down group is addressed elsewhere.

2.1 Subjects

A total of 24 subjects (10 men, 14 women) participated in the experiment. There were no significant differences between groups in age, height, weight or BMI (table 1).

Table 1. Subject characteristics

Group	Warm-up group	Control group	P-value
Age (years)	23.17 ± 2.89	23.33 ± 2.93	0.890
Height (Meters)	1.76 ± 0.11	1.69 ± 0.10	0.117
Weight (Kilograms)	72.83 ± 12.09	69.33 ± 18.90	0.595
Body mass index	23.22 ± 1.81	23.88 ± 4.81	0.662

Data are mean values ± SD. P<0.05 is considered as significant difference.

In order to get an equal gender distribution between the groups, men and women were separated before randomizing them into warm-up and control group. To participate in the experiment the subjects had to be healthy adults between 18 and 30 years of age without: current/recent back, hip or knee injuries, diseases that could lead to permanent harm and pregnant women. Subjects who had been training lunges or squats regularly during the last 3 months were excluded as well. All subjects were instructed to refrain from physical activity (above low intensity everyday activities) the day before, and during the test period. All subjects signed an informed consent scheme before participating, and the experiment was approved by the local medical ethics committee.

2.2 Procedures

A schematic illustration of the study design is illustrated in figure 1. All subjects were tested on 3 subsequent days with a 24 ± 2 hours interval. Prior to exercise (day 1), information about age, height and weight was collected. Subsequently, pain was measured by means of rating on a visual analogue scale (VAS), prior to the measurement of the pressure pain threshold (PPT). Thereafter, the isometric maximal voluntary contraction force (MVC) of the mm. quadriceps femoris was determined with a force transducer. Following the MVC, the warm-up group carried out a 20 minute warm-up period on an ergometer bike prior to the eccentric exercise, while the controls continued directly with eccentric exercise. Twenty-four hours following exercise (day 2) and 48 hours following exercise (day 3) the measurements of VAS, PPT and MVC were repeated and carried out in the same order as day 1.

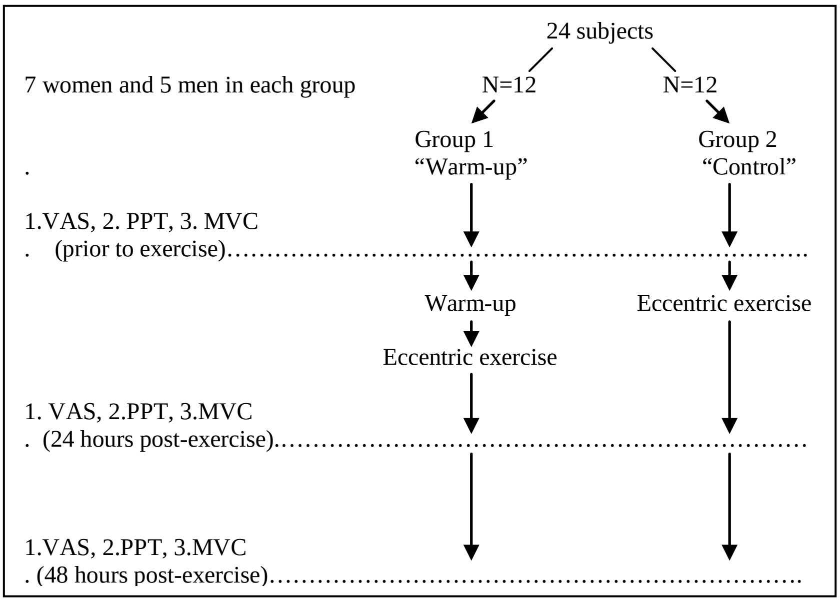

Figure 1. Schematic illustration of the study design. Pain was measured with a visual analogue scale (VAS), and an algometer (pressure pain threshold (PPT)) prior to the measurement of the isometric maximal voluntary contraction force (MVC). Outcome measures were collected prior to warm-up and eccentric exercise, 24 h and 48 h following exercise.

Visual analogue scale (VAS)

Following a 10 meter walk, the subjects were asked to rate the magnitude of pain they felt on the front side of the dominant thigh during the walk by rating the pain on a 100 mm VAS where 0 mm equals no pain, and 100 mm equals worst imaginable pain.

Pressure pain threshold (PPT)

A handheld electronic pressure algometer (Somedic Algometer type II, Sweden) was used to measure the PPT of 6 defined points on the m. rectus femoris of the dominant leg (figure 2). These PPT points were localized by measuring the distance from the anterior superior iliac spine (ASIS) to the superior border of the patella, and placing marks at 10, 20, 30, 40, 50 and 60 % of the distance starting from patella (10 % closest to patella, 60 % closest to ASIS).

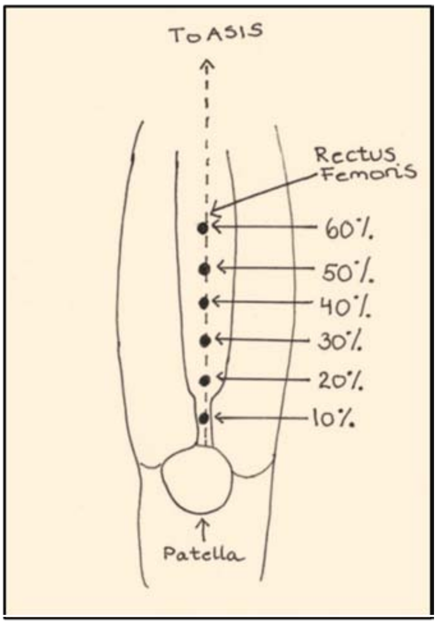

Figure 2. Illustration of pressure pain threshold locations on the m. rectus femoris.

Subjects were seated with a ~90º angle in knee and hip joint during marking and PPT measurement. The algometer had a 10 mm diameter rubber tip, which was applied to the defined points perpendicularly. The pressure was increased continuously by 40 kPa/s. The subjects were instructed to push a button to automatically stop the measurement when the pressure from the algometer changed from pressure to pain (minimum pressure sensed as pain). The PPT measurements were done in the same order on all subjects, starting on the mark 10 % distant from patella and continued chronologically with 20, 30, 40, 50, 60 % of the distance from patella to ASIS. Thereafter, the procedure was repeated in the same order. The average value of the two PPT measurements for each point was used in the analysis. For safety and accuracy reasons the maximal pressure applied was 1700 kPa.

Maximal voluntary isometric contraction force (MVC)

In addition to the pain measures, the subjects completed 3 isometric MVCs (on each day) with their dominant leg. The subjects were seated in a chair of a dynamometer (Biodex Medical Systems, Shirley, NY) and fastened by one belt over the hip and one over the dominant thigh. The chair was adjusted in such a way that hip and knee angles were 90º. A strap attached to a force transducer (interface Inc, Scottsdale, Arizona) was placed around the subjects' ankle, over the lateral malleolus. The subjects completed 3 MVCs lasting for 5 seconds, with 1 minute recovery between each contraction. During the MVC test, the subjects held their hands on the handles of the dynamometer, and they got visual feedback of the force development on a screen in front of them. An average of the peak value for each of the 3 MVCs was calculated for each day, and used in the analysis.

Eccentric exercise

In order to induce DOMS the subjects carried out 5 sets of 10 forward lunges with 30 second rest between each set. External resistance was applied by carrying a barbell on the subjects' shoulders, and was 40% of the total body weight for women and 50 % for men. The external resistance was based on results from pilot testing.

Prior to the forward lunges, the subjects were instructed in how to execute the exercise. Subjects were told to start in an upright position (figure 3A), with their legs fully extended, and upper body perpendicular to the ground. Thereafter, the subjects took a step forward (Figure 3B) with their dominant leg, and immerged until the angle of the dominant knee was 90º, and the dominant thigh was parallel to the floor (Figure 3C). Then the subjects got back to an upright position by using their dominant leg.

A. **B.** **C.**

Figure 3. Illustration of forward lunges. See text for more detail.

The starting position and landing position of the dominant leg was marked with a tape in order to standardize the execution of the exercise. Subjects were instructed to keep their bodies perpendicular to the ground during the entire movement. All subjects were allowed to practice a few times with and without external resistance before starting the exercise.

A metronome was used to indicate the tempo (22 repetitions per minute) of the forward lunges. Divergence from the tempo was commented, and corrected by the subject. If the subject could not finish all 5 sets with the pre-defined weight, the weight was slightly reduced.

Warm-up
In addition to the procedures described above, the warm-up group cycled for 20 minutes immediately prior to the forward lunges. Cycling was done on an ergometer bike (Monark 939E,Vansbro, Sweden) at an intensity of 60-70 % of the subjects' estimated maximal heart rate (220 minus age), and with a cycle cadency of 70 ± 5 repetitions per minute. Heart rate was measured with a heart rate monitor (*Polar RS800, Kempele, Finland*)

2.3 Statistical analyses

Statistical package for the social science version 17 (SPSS inc. Chicago) was used for analysis. An independent – samples T-test was used to compare the subjects' descriptive characteristics, and to compare differences between groups in baseline values for PPT and MVC.

For the PPT and MVC analysis, a mixed design model (2x3) for analysis of variance (ANOVA) was used to assess the impact of warm-up compared to no warm-up on force development and pain, across the 3 time periods (day 1, day 2 and day 3). This analysis tests for an interaction effect between the dependent variables (PPT and MVC) and the independent variables (warm-up/no warm-up) over time. When the analysis showed a significant main effect, a simple (first) contrast was used to compare the baseline values at day 1 to the values obtained on day 2 and day 3, to find where the differences were. If Mauchly's test of spherecity was violated ($P < 0.05$) for the main effect analysis, Greenhouse-Geisser adjusted significance was used.

A paired – samples T-test was used to check for differences in PPT and MVC within group between the 3 test days. Paired – samples T test was also used to compare means of PPT within groups at different locations (figure 2) at the same point of time.

PPT data violated the assumption of normal distribution, thus a logarithmic function (log 10) was used to obtain normal distribution. In the PPT analysis logarithmic transformed values were used, however in the tables and figures real values are used. All PPT analysis were conducted with both non-normal distributed real values, and logarithmic transformed values. The results revealed only minor differences between the real values and the logarithmic values, therefore we focus on the real values in the reminder of the text. MVC and PPT results are represented as means with a 95 % confidence interval (CI), and statistical significance level was set at $P < 0.05$.

VAS data violated the test of normal distribution, thus non-parametric tests were used for the analysis. A Mann-Whitney U test was used to test for differences between groups and a Friedman test was used for testing within group effects. If the results for the Friedman test were significant at $P < 0.0167$, a Wilcoxon signed rank test was performed to specify where the differences were. The VAS results are presented as median (50th percentile) values with 5th and 95th percentiles, and significance level set at $P < 0.05$.

3. Results

None of the subjects claimed to be fatigued following the warm-up. All subjects completed 5 full sets of forward lunges, and there were no differences between the groups in the relative external load. No significant differences between the groups were found in baseline measurements for any of the dependent variables (PPT, VAS and MVC). Furthermore, no significant differences were found either between groups on day 2 and day 3 or within groups between day 2 and day 3 in any of the dependent variables (PPT, VAS and MVC). Thus, all results are based on the analysis of day 2 and 3 when compared to day 1. For more clarity, mean values and 95 % confidence interval for MVC and PPT are illustrated in figure 4.

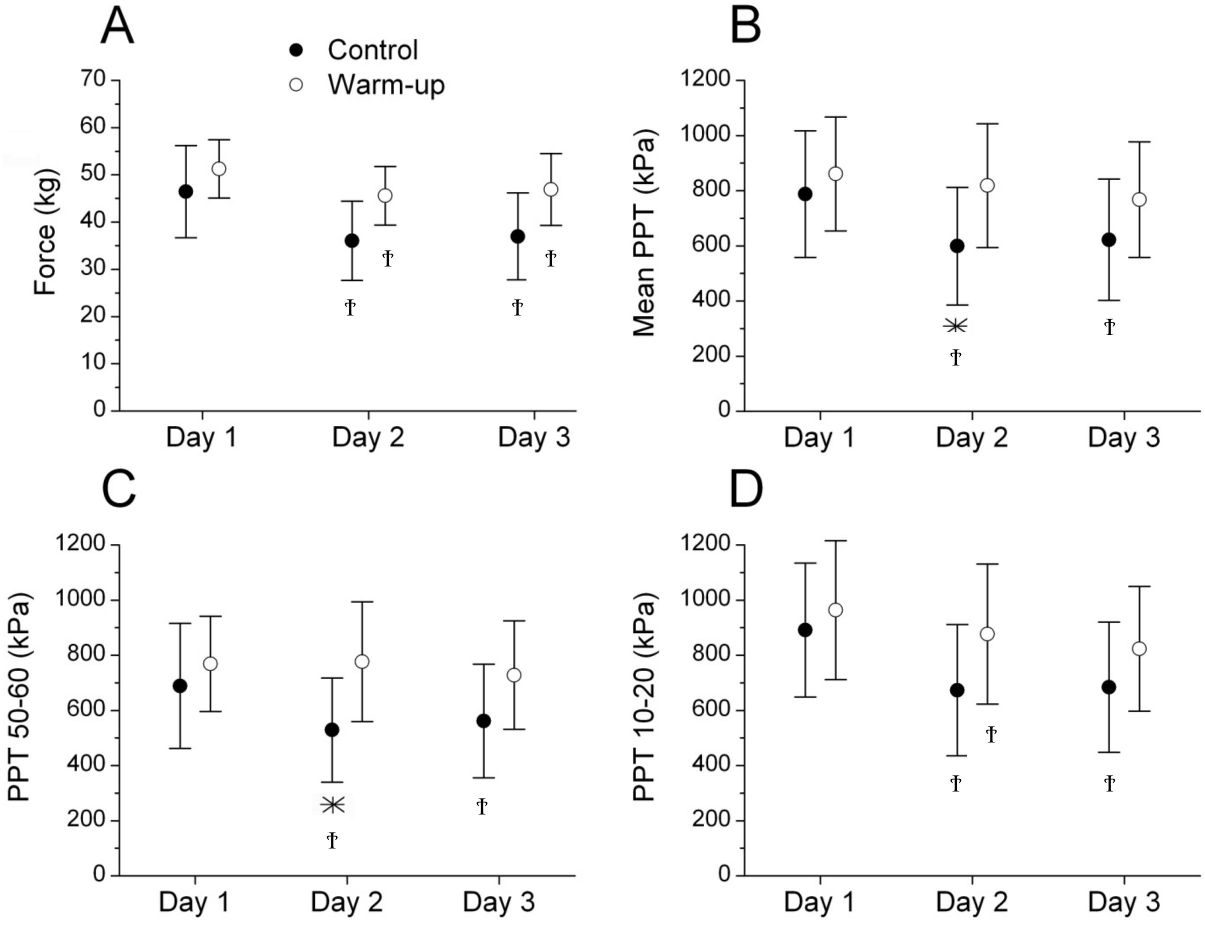

Figure 4. ✳ = significant ($P<0.05$) change from day 1 between groups. † = significant change from day 1 within group. Figures are presented with mean group values and a 95 % CI for both groups prior to exercise (day 1), 24 h following exercise (day 2) and 48 h following exercise (day 3). Figure A illustrates maximal voluntary contraction force (MVC). Figure B illustrates mean value of pressure pain threshold (PPT) measurements done on 10-60 % of distance from patella to ASIS, Figure C illustrates mean value of PPT measures done on 50 and 60 % of distance from patella to ASIS. Figure D illustrates mean value of PPT measures done on 10 and 20 % of distance from patella to ASIS.

The PPT data in the figures is not presented as log 10 values but as real values. However, statistical analysis is based on the log values for the variables that violated the normal distribution.

3.1 Maximal voluntary isometric contraction force (MVC)

One control subject did not complete all MVCs, and was therefore excluded from the MVC analysis. Thus, there were 12 warm-up subjects and 11 control subjects in the MVC analysis. Both groups had a significant (P< 0.024) decrease in MVC (figure 4A) on day 2 and day 3, when compared to day 1. However, no significant interaction of treatment group by time was found between the groups (P=0.062).

3.2 Pressure-pain threshold (PPT)

There were no significant differences within the groups in PPT measured at 10 % and 20 % of the distance from patella to ASIS when they were compared at the same point in time. Thus, an average of the 2 measurements was used in the analysis ($PPT_{10\text{-}20\%}$). The same applies for PPT at 50 % and 60 % of distance from patella to ASIS. Thus, an average of PPT 50 % and PPT 60 % were used in the analysis ($PPT_{50\text{-}60\%}$). PPT_{mean} represents an average of PPT measurements of all locations (10, 20, 30, 40, 50, 60% of distance from ASIS to patella)

There was no significant change in PPT_{mean} (figure 4B) within the warm-up group on day 2 (P=0.074) and day 3 (P=0.169), when compared to day 1. However, the control group had a significant decrease in PPT_{mean} on day 2 (P<0.001), and day 3 (P=0.001) when compared to day 1. There was significantly less reduction in PPT_{mean} between day 1 and day 2 in the warm-up group compared to the control group (P=0.001). However, this effect was not significant between day 1 and day 3 (P=0.169).

There was no significant change in $PPT_{50\text{-}60\ \%}$ (figure 4C) within the warm-up group on day 2 (P=0.434) and 3 (P=0.296), when compared to day 1. The control group had a significant decrease in $PPT_{50\text{-}60\%}$ on day 2 (P=0.002), and day 3 (P=0.007) when compared to day 1. Similar to PPT_{mean}, the control group decreased their $PPT_{50\text{-}60\%}$ significantly more than the warm-up group (P=0.004) between day 1 and day 2 (P=0.004). Between day 1 and day 3 there was no significant difference (P=0.125) between groups.

The warm-up group had a significant decrease in $PPT_{10\text{-}20\%}$ (figure 4D) on day 2 (P=0.040), but not on day 3 (P=0.125) when compared to day 1. The control group had a significant decrease in $PPT_{10\text{-}20\%}$ on day 2 (P<0.001) and day 3 (P<0.001) when compared to day 1. In contrast to PPT_{mean} and $PPT_{50\text{-}60\%}$, no significant interaction of treatment group by time was found between the groups (P=0.069 Greenhouse-Geisser)

3.3 Visual analogue scale (VAS)

Prior to exercise, none of the subjects reported any DOMS on the VAS (table 2) following a 10 meter walk. Both groups had significantly higher VAS ratings (more pain) within the group on day 2 and day 3, when compared to day 1. However, there were no significant differences between the groups in VAS ratings on day 2 (P=0.263) or on day 3 (P=0.067).

Table 2. Median values for visual analogue scale

Group	Median Day 1	5 ‰	95 ‰	Median Day 2	5 ‰	95 ‰	**P 1-2**	Median Day 3	5 ‰	95 ‰	**P 1-3**
WU	0	0	0	3.5	0	26	**0.018**	1.5	0	27	**0.012**
CON	0	0	0	14.5	0	24	**0.007**	13.5	0	40	**0.005**

Median values and 5th and 95th percentile (‰) for VAS prior to exercise (day 1), 24 h following exercise (day 2), and 48 h following exercise (day3). WU = warm-up, CON = control, *P 1-2* = significance value within group between day 1 to day 2, *P 1-3* = significance value within group between day 1 to day 3.

4. Discussion

The aim of this experiment was to investigate if a warm-up period, compared to no warm-up, has a preventive effect on the increased sensitivity to pain and the loss of force associated with DOMS. Our results indicate that warm-up might have a preventive effect on DOMS following eccentric exercise based on the preventive effect of warm-up that was found for PPT_{mean} and $PPT_{50\text{-}60\%}$ 24 hours following exercise. Although a same tendency in the response was seen for $PPT_{10\text{-}20\%}$ and MVC, these were not significant (P=0.069 and P=0.062, respectively). The VAS results showed a tendency for an effect of warm-up (P=0.067) 48 hours following exercise.

4.1 Evaluation of the interventions

The control group had a significant loss of force (MVC) and was significantly more sensitive to pain (PPT and VAS) on day 2 and day 3, when compared to day 1. This is in accordance with other findings (Hedayatpour et al., 2008). Thus, an external resistance of 50 % of bodyweight for men, and 40 % of bodyweight for women seems to be sufficient resistance in a group of healthy young adults to induce DOMS, if the practitioner is unaccustomed to the exercise.

The cycle intensity (60-70 % of estimated maximal heart rate) and duration (20 minute) that was used in the warm-up group was chosen to elevate muscle temperature as much as possible, without resulting in fatigue or lactate accumulation. We did not measure blood lactate concentration or muscle temperature during the warm-up. However, it has been shown that an intensity of 60-70 % of maximal heart rate eliminates lactate at the highest level (Hermansen and Stensvold, 1972), and that muscle temperature elevates the first 10-20 minutes of exercise (Saltin et al., 1968). None of the subjects claimed to be fatigued following the warm-up, and there were no differences between the groups in the relative external load or the repetitions of the eccentric exercise. Thus, we can anticipate that the warm-up in the present experiment elevated muscle temperature, without resulting in fatigue.

4.2 Effect of warm-up on Pressure-pain threshold (PPT) and force

DOMS is associated with an increased sensitivity to palpation (Nosaka et al., 2002). Previous experiments which have investigated the PPT in the m. rectus femoris have found a significantly lower pain threshold following eccentric exercise (Hedayatpour et al., 2008; Jönhagen et al., 1999). The results from the control group in our experiment support these findings. The control group had significantly more pain measured as PPT_{mean} and $PPT_{50\text{-}60\%}$

(proximal region) on day 2 and day 3, when compared to day 1. In contrast, the warm-up group did not have a significant change in PPT_{mean} and $PPT_{50-60\%}$ following eccentric exercise. In addition, when we compared the two groups we found that the warm-up group developed significantly less pain than the control group between day 1 and day 2. Experiments using similar techniques to quantify pain (applying pressure to the sore muscle) have found a preventive effect of warm-up on DOMS (Law and Herbert, 2007; Nosaka and Clarkson, 1997). Thus, based on our results and results from others, we suggest that warm-up prior to eccentric exercise might reduce some of the pain associated with palpation/pressure when DOMS is induced.

In contrast to the pain threshold measured as PPT_{mean} and $PPT_{50-60\%}$ we did not find a significant difference in development of pain between groups in the distal ($PPT_{10-20\%}$) region of the muscle, although the response showed a similar tendency. Additionally, the $PPT_{10-20\%}$ measurement was the only location where the pain threshold measurement in both groups showed a significant decrease between day 1 and day 2. This is in agreement with Hedayatpour and co-workers (2008) who reported a larger decrease pain threshold following eccentric exercise in the distal region of m.vastus lateralis, m.vastus medialis and m.rectus femoris, when compared to the proximal region.

A higher density of fast twitch fibers has been reported in the distal region of the quadriceps compared to the proximal region (Travnik et al., 1995). Fast twitch fibers are assumed to be more susceptible to damage following eccentric exercise than slow twitch fibers (Takekura et al., 2001). It has been postulated by Proske and Morgan, (2001) that muscle damage due to eccentric exercise leads to a release of Ca^{2+} in the sarcoplasm. The increased Ca^{2+} levels can trigger proteolysis and assist in the brake down of the damaged muscle fibers and possibly lead to muscle fiber necrosis. Moreover, damage due to increased myoplasmatic Ca^{2+} levels can lead to inflammation, resulting in edema and muscle swelling (Proske and Allen, 2005; Proske and Morgan, 2001). The inflammation is assumed to sensitize the nociceptors and lead to pain in the affected area (MacIntyre et al., 1995; Smith, 1991).

Our results indicate that the possible preventive effect of warm-up is more pronounced in the proximal region of the m. rectus femoris than the distal region. It is possible that this difference in pain development may have been caused by more muscle damage in the distal region because of the high density of fast twitch fibers. The results from our MVC analysis might provide some support to this suggestion.

Prolonged loss of force has been claimed to be the best indirect marker of muscle damage (Warren et al., 1999). In our experiment both groups had a significant decrease in MVC the two days following exercise. However, there was a non-significant (P=0.062) tendency of a larger decrease in the control group than in the warm-up group. This tendency might provide a vague indication of more muscle damage in the control group. However, if prolonged loss of force can provide an indication of the magnitude of muscle damage, the significant loss of force indicates that both groups may have experienced muscle damage. Further on, this might support the suggestion that the fast twitch fibers in the distal region of the muscle experienced more damage than the slow twitch fibers. Since fast twitch fibers are associated with a greater force output than slow twitch fibers (Enoka, 1995), it might be that the loss of force was a result of damage to the contractile elements which generates the most force. However, indirect markers of muscle damage cannot be used as evidence for muscle damage (Fridén and Lieber, 2001). Experiments investigating the effect of warm-up using histological methods to evaluate muscle damage are needed to confirm/reject this hypothesis.

4.3 Possible mechanisms of warm-up

The mechanism by which warm-up might reduce the pain sensation following eccentric exercise remains uncertain. As suggested in the introduction, it is possible that a severe warm-up would elevate muscle temperature, and that the elevation in temperature could result in less muscle damage resulting from overstretched muscles. Based on our results, it is our opinion that the severity of the warm-up in the present experiment might have been an important factor in obtaining a potentially beneficial effect on DOMS. Comparable experiments have provided results which might support this suggestion. High and co-workers (1989) found no effect of warm-up after 10 minutes of stepping exercise with an intensity of 2.7 METs (considered as light intensity (Jetté et al., 1990)). On the other hand, Law and Herbert (2007) found a preventive effect of 10 minute warm-up (walking) with an intensity of 3.1-3.4 METs (considered as moderate intensity (Jetté et al., 1990)). Due to the similarities of the experiments some of the differences in outcome might be due to the intensity of the warm-up. However, other mechanisms by which warm up could have a preventive effect on DOMS have been suggested as well.

Davis and co-workers (2008) hypothesized that increasing heart rate prior to eccentric exercise increases blood flow to the muscles, and thus decreases the muscle lactate concentration, and enhances nutritional supply. The increase in heart rate is expected to increase muscle perfusion which is assumed to reduce the cellular destruction, accelerate tissue repair, and thus limit inflammation and DOMS (Davis et al., 2008). However, this theory lack of scientific evidence. If elevated lactate concentration and lack of nutrition were to cause DOMS, one would suggest that the higher metabolism associated with concentric exercise also would cause DOMS. However, this does not seem to be the case (Walsh et al., 2004; Armstrong et al., 1983; Asmussen, 1956). Lactate concentration seems to return to resting levels within 90 minutes following severe exercise (Karlsson and Saltin, 1971), thus it is unreasonable to believe that lactate can cause the pain peaking 24-72 hours following the eccentric exercise. Further on, Davis and co-workers (2008) suggested that the increased blood flow would accelerate tissue repair and thus limit inflammation and DOMS. If this was the case it would be reasonable to believe that increasing blood flow by conducting a recovery period immediately following eccentric exercise could have a similar effect. So far, experiments investigating the effect of an active recovery have shown no treating effect on DOMS (Law and Herbert, 2007; Gulick et al., 1996). Based on current knowledge, we believe the possible preventive effect on DOMS found in the present experiment is more likely to be due to preventing muscle damage by elevated muscle temperature rather than removal of waste products and faster tissue repair.

4.4 Effect of warm-up on pain measured with a visual analogue scale (VAS)

Although there seemed to be a tendency in favor of a preventive effect of warm-up on VAS between the groups on day 3 (P=0.067), we found no significant effect of warm-up between the groups. Previous experiments have found conflicting results regarding the preventive effect of warm-up measured with VAS. Some have reported no effect of warm-up (Evans et al., 2002; High et al., 1989), while others claim to have found a preventive effect (Law and Herbert, 2007; Nosaka and Clarkson, 1997). Our results, and the conflicting results found by others does not allow us to conclude regarding the effect of warm-up on DOMS measured with VAS. Questions have been raised concerning the sensitivity of measuring DOMS with a VAS (Cleather and Guthrie, 2006; Nosaka et al., 2002).

4.5 Quantifying pain: VAS vs.PPT

The results in this experiment indicate that VAS and PPT measurements are not in accordance. As mentioned, we found a significant effect of warm-up on pain measured as PPT while no significant effect was found with VAS. Based on our results it is our opinion that our PPT results provide a more reliable result than the VAS. This is based on 2 assumptions: *First;* It has been suggested that PPT offers a more objective quantification of pain than the VAS (Warren et al., 1999). In our experiment, the subjects were instructed to stop the PPT measurement themselves when they felt the minimum pressure sensed as pain. Thus, their individual pain threshold was the basis for the analysis, and the pain threshold could both increase and decrease the following day[1]. Regarding the VAS, all subjects reported no pain (0 mm) prior to the eccentric exercise. Accordingly, all subjects reported to have the same experience of pain, and due to the nature of the VAS, pain could only increase the following day. Following the eccentric exercise the experience of pain may wary between subjects. While some might have rated 50 mm. on the VAS if their pain were medium, others might have rated 30 mm. even if their pain was severe. Because of the subjective experience of pain measured with VAS the question arises whether it is suitable to quantify DOMS in a relatively small group. *Second;* The VAS provides a general subjective experience of the total pain experienced by the subject. However, it is not suitable to distinguish between different compartments of the muscle. On the other hand, PPT measured with an algometer discriminates different parts of the muscle, and consequently gives more specific information regarding the magnitude of pain in the different regions. Thus, we believe VAS and PPT complement each other by providing different information when quantifying DOMS. However, the PPT seems to provide more specific information regarding the location of the pain.

4.6 Limitations and recommendations

Two subjects experienced bruising as a result of the PPT measurements. It is known that pressure can cause damage to blood vessels and lead to an inflammation and bruises (Pilling et al., 2010), and consequently lead to pain (Woolf, 2004). Therefore, caution must be taken when pain is measured with an algometer. The pain from the bruises could lead to an overestimation of the pain from the DOMS, and thus confound the results. However, in our experiment only one subject in each group experienced bruises, thus we believe they did not influence the final result.

In our experiment the gender distribution was similar between groups. Studies have shown a similar relative decrease in loss of force and increased sensitivity to pain between genders following eccentric exercise (Nie et al., 2007). However, in general women seem to report more pain and generate less force than men prior to, and after DOMS is induced (Dannecker et al., 2005; Nie et al., 2007). Thus, having both genders in the same group might have

[1] One subject in each group reached the upper plateau (1700 kPa) for the $PPT_{10\text{-}20\%}$, and could therefore not increase the pain threshold the following day.

increased the variability within the groups for both pain and MVC, thereby decreasing the power to find a significant difference between the groups. Thus, it might be desirable to investigate preventive and treating effects of DOMS in groups with only men or women.

In this thesis we have indicated that a severe warm-up might provide more protection against DOMS than a mild warm-up. We suggested that a possible mechanism for this preventive effect is due to elevated muscle temperature, resulting in less muscle damage. However, the differences between experiments investigating the effect of warm-up on DOMS might be a result of different interventions to induce DOMS. It is reasonable to believe that a severe eccentric exercise would affect the magnitude and progress of pain differently than a mild eccentric exercise. Thus, a standardized protocol to induce DOMS would be desired to eliminate this source of error. In addition, further experiments are needed to evaluate the effect of different durations and intensities of warm-up in regard to the magnitude of DOMS and muscle damage.

5. Conclusion

A warm-up period prior to eccentric exercise seems to prevent some of the harmful effects associated with DOMS. Our results indicate that the preventive effect, measured as pressure-pain threshold, is larger in the proximal region of the muscle than the distal region 24 hours following exercise. No significant effect of warm-up was found when pain was measured with a visual analogue scale. However, it is our opinion that the pressure-pain threshold provides a more reliable result than the visual analogue scale.

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