

## Running versus strength-based warm-up: acute effects on isometric knee extension function

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**Abstract** This study investigated the influence of two warm-up protocols on neural and contractile parameters of knee extensors. A series of neuromuscular tests including voluntary and electrically evoked contractions were performed before and after running- ( $R_{WU}$ ; slow running, athletic drills, and sprints) and strength-based ( $S_{WU}$ ; bilateral 90° back squats, Olympic lifting movements and reactivity exercises) warm ups (duration ~40 min) in ten-trained subjects. The estimated overall mechanical work was comparable between protocols. Maximal voluntary contraction torque (+15.6%;  $P < 0.01$  and +10.9%;  $P < 0.05$ ) and muscle activation (+10.9 and +12.9%;  $P < 0.05$ ) increased to the same extent after  $R_{WU}$  and  $S_{WU}$ , respectively. Both protocols caused a significant shortening of time to contract (−12.8 and −11.8% after  $R_{WU}$  and  $S_{WU}$ ;  $P < 0.05$ ), while the other twitch parameters did not change significantly. Running- and strength-based warm ups induce similar increase in knee extensors force-generating capacity by improving the muscle activation. Both

protocols have similar effects on M-wave and isometric twitch characteristics.

**Keywords** Warm-up · Electromyography · Electrical stimulation · Central activation · Muscle contractile properties

### Introduction

Active warming-up (WU) is a common practice preceding nearly every athletic event. This routine is believed to be essential for injury prevention and performance enhancement; a point of view that is supported by empiric observations and by a large number of scientific studies (Burkett et al. 2005; Gourgoulis et al. 2003; McBride et al. 2005; Saez Saez de Villarreal et al. 2007; Vetter 2007; Yetter and Moir 2008). The potential beneficial mechanisms include an increase in muscle temperature or in nerve conduction rate, a speeding in oxygen kinetics due to the greater muscle perfusion, oxygen transport, and delivery and/or a decrease in viscous resistance and stiffness (Bishop 2003; Jones et al. 2003).

Most active WU routines integrate four types of exercise: “cardiovascular” often based on running; “muscular” including some ‘explosive strength’ exercises; passive or active “stretching”; and “specific” (i.e., miming the characteristics of the event). The specificity of these exercises is a key point and most of them are miming some aspects (e.g., posture, rhythm, muscular action, inter-limb coordination, angular displacement) of the competitive event or a part of it. However, the optimal modalities are still highly debated (Bishop 2003; Woods et al. 2007). For example, vertical jumping ability has been shown to improve following strength-related WU (Burkett et al.

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2005; Gourgoulis et al. 2003; Saez Saez de Villarreal et al. 2007), but deteriorated if WU includes some stretching (Holt and Lambourne 2008; Young and Behm 2003). Moreover, the detrimental effect of stretching during WU has been reported to be reversed (Stewart et al. 2007; Taylor et al. 2008a, b) or not (Pearce et al. 2009) if followed by a second bout of specific exercise. This might explain why it is so difficult to design the optimal (e.g., duration, intensity, recovery) WU routine that would be the perfect balance between benefits due to slight muscle temperature increase and neural adaptations without the detrimental effects of reduced muscle stiffness or contractility.

Evidence supporting the inclusion of various weight-training exercises during WU preceding speed/power events has grown in recent years. Supporting coaching viewpoints, several investigations have shown that the benefit of incorporating strength- or power-oriented drills into a standard WU protocol to increase subsequent vertical jump (Burkett et al. 2005; Gourgoulis et al. 2003; Güllich and Schmidtbleicher 1995; Koch et al. 2003; Radcliffe and Radcliffe 1996; Saez Saez de Villarreal et al. 2007) or sprinting (McBride et al. 2005; Vetter 2007; Yetter and Moir 2008) performance. In these studies, however, the underlying mechanisms of performance gains are sometimes speculative in the absence of investigation on the associated changes in the neural and muscular systems.

Percutaneous nerve stimulations, that usually associate electromyography and measurements of voluntary and evoked forces, have been used in humans as a reliable approach to assess the adaptations that occur within the neuromuscular system after fatigue (Girard et al. 2008), training (McKenna et al. 1993) or hyperthermia (Racinais et al. 2008). The usefulness of this technique is that it integrates measures of neural activation and intrinsic muscular properties. To the best of our knowledge, however, the study by Skof and Strojnik (2007) is the only one that has used successfully this method to compare the effect of two different WU routines—i.e., one of the protocols consisted of jogging and stretching only while the other also included different bounding and sprinting exercises—in seven well-trained middle distance runners. To date, the acute effect of running- and strength-based WU routines on the neuromuscular system (and the likely difference between these two forms of WU protocols) has yet to be determined. Furthermore, since the number of motor units recruited during exercise depends mainly on the level of force exerted loading exercises must induce larger motor unit recruitment than unloading exercises (Kram and Taylor 1990). Consequently, one could hypothesize that weight-lifting-oriented-WU would induce a larger motor unit recruitment and a more efficient effect than unloading exercise oriented-WU composed of running and athletic drills.

The aim of this study was, therefore, to investigate some of the mechanisms that contribute to the acute changes in neuromuscular function following two types (running- vs. strength-based) of warm-up protocols. It was hypothesized that both WU protocols induce higher neural activation and improved contractile parameters of knee extensors, with more marked adaptations following the modality incorporating weight-training exercises.

## Methods

### Subjects

Ten male sport science students (mean  $\pm$  SD age 22.7  $\pm$  2.2 years; mass: 78.2  $\pm$  11.0 kg; stature: 1.80  $\pm$  0.10 m) volunteered to participate in the study after they were informed in detail about the nature of the experiment and possible risks. These individuals were engaged in intermittent sports (soccer, rugby, tennis, badminton) for at least 5 years. The mean time spent in training during the 6 months preceding the experiments was 10.2  $\pm$  5.5 h week<sup>-1</sup>. All subjects were performing regularly aerobic exercises, repeated sprints, plyometric and resistance exercises in their training routines. They were tested at the midpoint of the season. All subjects provided written informed consent and the local Committee on Human Research gave its approval for the project.

### Procedures

#### *Preliminary session*

Two to three days before starting the experiment, subjects were asked to come to the laboratory for a familiarization session to be accustomed with the testing procedures and to allow determination of the optimal electric stimulation intensities. Each subject first carried out a standardized WU. It consisted of 5 min of running at a self-selected pace (8–10 km h<sup>-1</sup>), followed by ten isometric knee extensions (alternating 4 s of contraction and 6 s of rest). Subjects were instructed to increase progressive contraction intensity in order to reach the maximal levels during the last three trials. Subsequent to this WU, subjects were familiarized with several sub-maximal electrical stimuli. They were then requested to perform knee extensors (KE) maximal voluntary contractions (MVC) until they felt accustomed to the equipment; the coefficient of variation in three successive trials was <5%. Afterwards, the stimulation intensity required to elicit a maximal M-wave response was determined (see stimulation). Thereafter, subjects performed the complete procedure of neuromuscular tests. Following the neuromuscular testing, all subjects were tested for their 90°

back squat one repetition maximum (1RM) according to the procedures outlined by McBride et al. (2002); this value ( $145 \pm 25$  kg) was used in applying the appropriate load in the subsequent WU procedure.

### Testing sessions

The subsequent test sessions were conducted as follows with 5–7 days apart: (1) preparation of the subject (electrode placement, verification of the signals and stabilization of the values;  $\sim 10$  min), (2) pre-WU neuromuscular tests ( $\sim 5$  min), (3) running- ( $R_{WU}$ ) or strength-based ( $S_{WU}$ ) WU trials ( $\sim 40$  min) in a random order, and (4) post-WU neuromuscular tests ( $\sim 5$  min). Efforts were made to avoid caffeine intake and to ensure that no strenuous exercise was performed in the 24 h that preceded testing, which took place at the same time of day. The air temperature was  $\sim 22^\circ\text{C}$ .

### Warm-up protocols

#### Running-based warm-up

The  $R_{WU}$  began with slow running ( $8\text{--}10$  km h $^{-1}$ ) for  $\sim 10$  min. This was followed by 30 m athletic drills for  $\sim 15$  min ( $2 \times$  heel flicks,  $2 \times$  high knees,  $2 \times$  skipping,  $2 \times$  coordination skips,  $2 \times$  hopping) with 90 s recovery between sets. Finally, subjects were requested to perform maximal sprints ( $3 \times 60$  and  $5 \times 15$  m acceleration runs with 90 s and 2 min recovery periods between repetitions, respectively;  $\sim 15$  min). All athletic drills were performed on a 200 m indoor track in tartan.

#### Strength-based warm-up

The  $S_{WU}$  consisted of strength exercises that involved an alternation of heavy and light loads. Subjects first performed bilateral half ( $90^\circ$ ) back squats while holding a barbell across their shoulder [3 sets  $\times$  (3 repetitions at 90% of the predetermined 1RM followed by a set of 6 repetitions at 30%)]. This was followed by Olympic lifting movements [clean and snatch; 3 sets  $\times$  (6 repetitions at 30 kg followed by a set of 6 repetitions at 20 kg) each]. Two minutes rest intervals were given between each set of strength exercises, while a  $\sim 5$  s rest interspersed repetitions. All light load repetitions were executed as quickly as possible. Finally, reactive running ( $4 \times 10$  m) drills were performed with 1 min recovery between efforts.

### Mechanical work quantification

The  $R_{WU}$  and  $S_{WU}$  took  $\sim 40$  and  $\sim 43$  min, respectively. The overall mechanical work performed was adjusted

carefully to be similar between the two WU treatments ( $3,186 \pm 7$  vs.  $3,185 \pm 6$  J kg $^{-1}$  for  $R_{WU}$  and  $S_{WU}$ , respectively). The work was calculated from the estimated horizontal and vertical displacement of the center of mass during each running exercise (e.g., drills) (Arsac and Locatelli 2002):

$$W_{\text{running}} = (C d m \eta + 1/2 m (V_{\text{max}}^2 - V_{\text{min}}^2)) n$$

$$W_{\text{drill}} = (m g \Delta H + 1/2 m (V_{\text{max}}^2 - V_{\text{min}}^2)) n$$

where  $C$  is the energy cost of running at constant speed ( $4$  J kg $^{-1}$  m $^{-1}$ ),  $d$  is the distance covered expressed in m,  $\eta$  (0.50) is the muscular efficiency of running,  $m$  is the body mass expressed in kg,  $g$  is the gravitational acceleration expressed in m s $^{-2}$ ,  $V_{\text{max}}$  and  $V_{\text{min}}$  are the maximal and minimal velocities of the center of mass,  $\Delta H$  is the center of mass displacement expressed in m and  $n$  is the number of repetition.

For the strength exercises, the vertical displacements of both the center of mass of the subject and the bar were used to calculate the work:

$$W_{\text{strength}} = (m g \Delta H) n$$

where  $m$  is the moved mass expressed in kg,  $g$  is the gravitational acceleration expressed in m s $^{-2}$ ,  $\Delta H$  is the center of mass displacement expressed in m and  $n$  is the number of repetition.

### Neuromuscular tests

Neuromuscular test sessions began by eliciting three electrically evoked twitches at rest separated by 5 s. Thereafter, subjects were instructed to perform three KE MVC with doublets (two electrically evoked twitches, 10 ms apart) delivered over the isometric plateau (control doublet) and 4 s after each MVC (potentiated doublet), to assess voluntary activation (VA) level according to the twitch interpolation technique. Each MVC was approximately 4 s in duration and there was 60 s of rest between MVC trials. Strong verbal encouragement was given to the subjects during each maximal effort.

### Measurements

#### Torque measurement

Maximal voluntary contractions torque of the right KE muscles was measured through an isometric ergometer, which consisted of a chair connected to a strain gauge (Captels, St Mathieu de Treviers, France). Subjects were placed in a seated position and were securely strapped into the chair. Movements of the upper body were limited by two crossover shoulder harnesses and a belt across the

abdomen. The trunk-thigh angle was 90°. The axis of the dynamometer was aligned with the knee flexion-extension axis, and the lever arm was attached to the shank around the ankle with a strap. The knee angle was fixed at 80° of flexion (0° corresponding to full knee extension).

### Stimulation

Electrically stimulations were given using a high-voltage (maximal voltage 400 V) constant-current stimulator (model DS7AH, Digitimer, Hertfordshire, UK). The femoral nerve was stimulated using a monopolar cathode ball electrode (0.5 cm diameter) manually pressed into the femoral triangle by the experimenter. The anode was a 50 cm<sup>2</sup> (10 × 5 cm) rectangular electrode (Medicompex, Ecublens, Switzerland) located in the gluteal fold opposite the cathode. During the preliminary tests, the amperage of a rectangular pulse (200 μs) was raised progressively (10 mA increment) until a plateau in both twitch and M-wave amplitude was observed. This intensity was further increased by 20% (e.g., supramaximal) and subsequently maintained for the entire session. We considered that this stimulation (70–160 mA) recruited all quadriceps motor units maximally and synchronously.

### Electromyography

The electromyographic (EMG) signal from the *vastus lateralis* (VL) and *vastus medialis* (VM) muscles was recorded bipolarly by silver chloride circular (interdistance electrode = 20 mm) surface electrodes (Contrôle Graphique Medical, Brie-Comte-Robert, France) fixed lengthwise over the middle of the muscle belly. The reference electrode was attached to the left wrist. Low impedance between the two electrodes (<3 kΩ) was obtained by abrading the skin with emery paper and cleaning with alcohol. Subjects kept the electrodes on their skin throughout the duration of the entire experiment; nevertheless, the position of the electrodes was marked because for some subjects electrodes had to be replaced because of excessive sweating. EMG signals were amplified and filtered (band-pass 30–500 Hz, gain 1,000) (Biopac MP30, Systems Inc., Santa Barbara, CA, USA).

### Data analysis

Torque and EMG traces were digitized online (sampling frequency 2,000 Hz), and stored for analysis with commercially available software (Acqknowledge 3.6.7, Biopac Systems Inc., Santa Barbara, CA, USA). For the MVC, the EMG of the VL and VM muscles was analyzed over a 1 s period when the torque had reached a plateau (before the superimposed doublet) to calculate the root mean square

(RMS<sub>VL</sub> and RMS<sub>VM</sub>, respectively). Raw RMS values were then normalized to respective maximal M-wave amplitudes (e.g., RMS/M ratio). Activation level was estimated according to the following formula: voluntary activation = [1 – (superimposed doublet/potentiated doublet)] × 100 (Allen et al. 1995).

For the electrically evoked contractions, the peak-to-peak amplitude and duration of M-waves responses were retained for both VL and VM muscles. The following parameters were quantified from the torque trace associated to single contraction: (1) peak torque (PT), e.g., the highest value of twitch tension production, (2) time to peak torque (TPT), e.g., the time from the origin of the twitch to the absolute PT, (3) half-relaxation time (HRT), e.g., the time to obtain half of the decline in maximal torque, (4) maximal rate of twitch force development (MRFD); e.g., maximal value of the first derivative of the torque signal and (5) maximal rate of twitch force relaxation (MRFR); e.g., lowest value of the first derivative of the torque signal. The average of three trials was used for further analysis.

### Statistical analysis

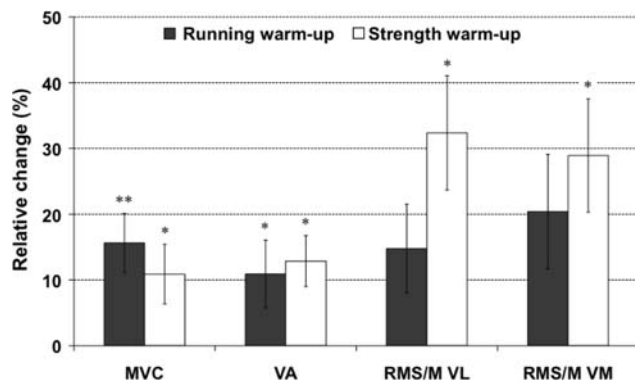
All data are expressed as mean ± SD. Changes in neuromuscular variables between WU treatments were determined using a two-way repeated measures ANOVA [time (pre- vs. post warming-up) × condition ( $R_{WU}$  vs.  $S_{WU}$ )] with Tukey post hoc test. In addition, relationships between variables of interest were tested using the Spearman's correlation coefficient. Statistical significance was accepted at  $P < 0.05$  for all procedures (SigmaStat, Jandel Corporation, San Rafael, CA, USA).

## Results

### MVC torque and muscle activation

There was a significant effect of time on MVC torque ( $P < 0.01$ ) and muscle activation parameters (VA, raw and normalized VM EMG activity,  $P < 0.05$ ; raw and normalized VL EMG activity,  $P < 0.01$ ). No significant main effect of condition or interaction effect between time and condition were found for these variables. MVC torque (from  $297.8 \pm 86.5$  to  $338.3 \pm 79.2$  Nm;  $P < 0.01$  and from  $318.1 \pm 94.6$  to  $346.4 \pm 83.6$  Nm;  $P < 0.05$ ) and VA (from  $78.0 \pm 14.9$  to  $85.1 \pm 7.6\%$  and from  $80.0 \pm 16.0$  to  $88.9 \pm 13.0\%$ ; both  $P < 0.05$ ) increased to the same extent after  $R_{WU}$  and  $S_{WU}$ , respectively (Fig. 1).

The changes in MVC and VA were highly correlated ( $r = 0.83$  and  $0.85$ ;  $P < 0.01$ ) and the raw EMG activity during MVC increased in VL (+18.6 and +22.2%;



**Fig. 1** Relative changes in MVC torque and muscle activation after the two warm-up protocols. *MVC* maximal isometric voluntary contraction of knee-extensor muscles, *VA* voluntary activation level (estimated by the twitch interpolation technique), *RMS/M VL* normalized EMG activity of the *vastus lateralis* muscle, *RMS/M VM* normalized EMG activity of the *vastus medialis* muscle. Values are mean ± SE (*N* = 10). There was a significant effect of time. \**P* < 0.05; \*\**P* < 0.01, for statistically significant differences between values recorded before and after the warm-up. No significant main effect of condition or interaction effect between time and condition were found

*P* < 0.01) and VM (+18.3 and +20.1%; *P* < 0.05) during *R<sub>WU</sub>* and *S<sub>WU</sub>*, respectively. RMS/M increased in the two *vastii* (+32.4 and +28.9% in VL and VM; both *P* < 0.05) for *S<sub>WU</sub>*, whereas did not change significantly for *R<sub>WU</sub>* (+14.8 and +20.4% in VL and VM, *P* = 0.32 and *P* = 0.07, respectively).

**M-wave and twitch contractile properties**

The effects of the two WU protocols on twitch mechanical parameters are displayed in Table 1. Both protocols induced a significant shortening of time to contraction (−12.8 and −11.8% after *R<sub>WU</sub>* and *S<sub>WU</sub>*; both *P* < 0.05),

while the other twitch parameters were not affected by the treatments.

M-wave duration in VM was decreased following *S<sub>WU</sub>*, whereas remained unchanged after *R<sub>WU</sub>*. M-wave amplitude in VL was smaller after *S<sub>WU</sub>* than after *R<sub>WU</sub>* (Table 2).

**Discussion**

**Maximal voluntary strength and activation**

In the present study, an 11–16% increase in KE MVC torque was measured after *R<sub>WU</sub>* and *S<sub>WU</sub>*, underlying an improved neuromuscular efficiency after the completion of both WU treatments. These findings are in-line with those reported recently by Skof and Strojnik (2007) who found an 16% increase in voluntary torque after the completion of a 25–27 min WU procedure incorporating slow running, stretching, bounding and sprinting exercises, whereas strength gains were rather modest (~5%) after a 15 min routine that involved slow running and stretching exercises only. However, direct comparison of the extent of strength gains observed between the present study and the one by Skof and Strojnik (2007) is only anecdotic since subjects’ characteristics and structure of the WU routines (i.e., duration, intensity, nature of exercises) vary considerably.

Although central adaptations following the completion of various WU protocols have been suggested for several years (Güllich and Schmidtbleicher 1995; Jones et al. 2003; Verkoshansky 1986; Young 1993), no evidence for an enhanced neural input to the working muscles has been published until recently (Skof and Strojnik 2007). In our experiment, the twitch interpolation technique was adopted to determine potential change in central drive. Although the maximal voluntary activation values estimated here might appear low (~78 to ~85% and ~80 to ~89% for

**Table 1** Effect of the two warm-up protocols on twitch contractile properties

Parameters	Running warm-up			Strength warm-up			Significant main effect
	Before	After	Changes (%)	Before	After	Changes (%)	
PT (Nm)	55.4 ± 10.7	56.1 ± 12.1	+2.0	58.2 ± 10.1	52.5 ± 4.3	−8.2	–
TPT (ms)	77.2 ± 11.9	66.5 ± 7.7*	−12.8	84.4 ± 14.6	72.0 ± 7.4 *	−11.8	T, C
HRT (ms)	85.3 ± 25.0	75.9 ± 9.9	−6.9	82.6 ± 22.7	70.5 ± 14.0	−11.1	–
MRFD (Nm ms <sup>−1</sup> )	2.18 ± 0.63	2.26 ± 0.75	+5.2	2.16 ± 0.60	2.01 ± 0.31	−2.9	–
MRFR (Nm ms <sup>−1</sup> )	0.86 ± 0.24	1.01 ± 0.19	+22.3	0.96 ± 0.25	1.00 ± 0.16	+9.2	–

Values are mean ± SE (*N* = 10)

*T* and *C* indicate significant main effects of time and condition

There was no significant interaction between time and condition

*PT* peak twitch, *TPT* time to peak twitch, *HRT* half-relaxation time, *MRFD* maximal rate of twitch force development, *MRFR* maximal rate of twitch force relaxation

\* *P* < 0.05, for statistically significant differences between values recorded before and after the warm-up

**Table 2** Effect of the two warm-up protocols on M-wave characteristics

Parameters	Running warm-up			Strength warm-up			Significant main effect
	Before	After	Changes (%)	Before	After	Changes (%)	
VL amplitude (mV)	10.02 ± 2.67	10.55 ± 2.93	+6.3	9.46 ± 3.16	8.72 ± 2.59 <sup>\$\$</sup>	-6.5	T
VL duration (ms)	5.92 ± 1.56	6.08 ± 1.10	+5.2	6.80 ± 2.70	6.63 ± 2.45	-0.8	-
VM amplitude (mV)	9.72 ± 3.67	9.89 ± 4.54	+1.6	8.42 ± 3.50	7.85 ± 3.21	-4.5	-
VM duration (ms)	4.53 ± 1.62	5.25 ± 2.12	+15.0	5.57 ± 2.68	4.37 ± 1.81*	-16.5	I

VL vastus lateralis, VM vastus medialis

Values are mean ± SE (N = 10)

T indicates a significant main effect of time

There was no main effect of protocol

\* P < 0.05, for statistically significant differences between values recorded before and after the warm-up

I denotes a significant interaction between time and condition

<sup>\$\$</sup> P < 0.01, for statistically significant differences between running- and strength-based warm-ups for values recorded after the procedure

$R_{WU}$  and  $S_{WU}$ , respectively), there are in-line with previous studies where incomplete activation of the KE muscles has also been reported (Girard et al. 2008; Skof and Strojnik 2007). An important result was also the strong correlation found between increases in MVC torque and muscle activation after each WU protocol. Taken together, these findings provide good evidence to postulate that KE are subject to an increased central outflow from pre- to post-treatments.

Surface EMG is the most commonly used electrophysiological technique to investigate neuromuscular activation (Farina et al. 2004). In-line with increased VA, strength gains measured after  $R_{WU}$  and  $S_{WU}$  were also accompanied by a significant increase in raw EMG activities of both *vastii*. Opposite results have been reported after a WU performed on a cycle ergometer at 70% of the ventilatory threshold (Stewart et al. 2003). Nevertheless, these findings must be considered cautiously, since an increase in RMS during MVC does not necessarily imply greater muscle activation because sarcolemmal excitability can be modified as well (Racinais et al. 2008). As a consequence, EMG activity values of both *vastii* were also normalized to the respective maximal M-wave (e.g., RMS/M ratio, Gandevia 2001). In the present experiment, the respective ~10–15% and ~25–35% increases in normalized RMS EMG activity noted after  $R_{WU}$  and  $S_{WU}$ , respectively, confirmed the potentially higher level of excitation of active VL and VM motor units. With identical overall work between the two WU routines, one may also argue that neural changes following  $S_{WU}$  were probably more pronounced, as increase in normalized EMG activities following  $R_{WU}$  did not reach significance.

As a whole, such enhanced voluntary activation after both WU routines indicates a larger motor unit recruitment and/or an increased firing rate. With neural indices (EMG activity and twitch interpolation results) used in this study

it is, however, not possible to clarify whether such central adaptations are accounted for by an increased neural drive from supraspinal centers or an enhanced excitation of the  $\alpha$ -motoneuronal pool (Gandevia 2001). It remains also conceivable that the increase neural drive to active muscles was due, at least partially, to a more synchronized discharge of the motor neurons (Farina et al. 2004). This phenomenon might be more marked in  $S_{WU}$  because including strength-oriented exercises in a training routine was shown to be associated with an increase in motor unit short-term synchrony (Milner-Brown et al. 1975).

#### Evoked contractions

As a measure of membrane excitability, we examined change in M-wave characteristics (Fuglevand et al. 1993). This approach has also been used previously to detect changes in the effectiveness of the action potential transmission/propagation in muscle fibers following fatigue (Girard et al. 2008), training (McKenna et al. 1993) or hyperthermia (Racinais et al. 2008). In the present study, the unchanged M-wave amplitude of both *vastii* after  $R_{WU}$  and  $S_{WU}$  (although post-WU M-wave amplitude in VL was smaller after  $S_{WU}$  than after  $R_{WU}$ ) indicates that action potential transmission was probably not affected by the treatments. Nevertheless, when investigating potential changes in sarcolemmal excitability from EMG recordings, we have also to consider that M-wave data can be affected by the synchronization of muscle fiber action potentials or the degree of dispersion in the release of transmitters from motor nerve terminals (Hicks et al. 1989).

Unexpectedly, minimal changes in peak twitch torque were found after both WU treatments. This result is not in good agreement with those showing that warming-up with explosive-strength exercises such as bounding and sprinting resulted in the potentiation of the contractile complex

of the skeletal muscle (Skof and Strojnik 2007). Previous studies have proposed that the balance between excitation (potentiation) and inhibition (fatigue) affecting muscular muscle contractile efficiency could be modulated by the duration or volume of the conditioning stimulus (Sale 2002). Therefore, the observed inconsistency of twitch results between the present study and the one by Skof and Strojnik (2007) may be, at least partially, linked to the relatively long duration ( $\sim 40$ – $43$  min) and high-intensity of the two WU routines proposed here. A precocious fatigue, most likely following  $S_{WU}$ , might have contributed to cancel out the expected amplified level of myosin cross-bridge activity. Again, an insufficient time for recovery from fatigue (i.e., time separating the end of the WU and testing procedures) cannot be ruled out to explain the modest changes in twitch contractile properties.

Another result of the present study is also that the reduction in TPT of the evoked twitch was similar ( $\sim 10\%$ ) between  $R_{WU}$  and  $S_{WU}$ . This result suggests an increased efficiency in the function of the sarcoplasmic reticulum, as TPT response is regulated by the rate of release of  $Ca^{2+}$  from the sarcoplasmic reticulum and/or its interaction with the regulatory protein troponin (Kugelberg and Thornell 1983). However, the rate at which the sarcoplasmic reticulum can sequester  $Ca^{2+}$  was probably not changed because no significant modification in HRT was observed pre- to post-WU procedures. Muscle temperature increases ranging from  $\sim 1$  to  $3^\circ C$  have been reported after WU (Magnusson et al. 2000; Skof and Strojnik 2007). Although not measured in this study, the probable rise in muscle temperature inducing a reduced inner passive muscle stiffness and/or an increased ATPase activity cannot be ruled out to explain, the observed shortening of muscle contraction (TPT) (Candau et al. 2003; Proske et al. 1993). It is well known that increase in muscle temperature might affect twitch force development (Ranatunga et al. 1987). Nevertheless, it should be noted that most of experiments studying those modifications were conducted at non-physiological temperatures. In the present study, the expected changes in electrically evoked isometric MRFD and MRFR have not been evaluated after both WU procedures. Increase in muscle temperature is closely related to the amount of mechanical work performed (Joule effect). In our study, the matching in mechanical work suggests that the temperature-related effects were probably similar and undetectable between the two WU protocols.

#### Methodological limitations

One major limitation of this study lies in the lack of muscle temperature measurements. As a result, the relative contribution of the temperature-induced factors following active WU performed here cannot be ascertained.

Nevertheless, one may reasonably argue that the shortening of TPT was a response of the neuromuscular system to muscle temperature rise (Bishop 2003). In this view, a correlation between reduced TPT and increased skin temperature on the surface of the *vastus lateralis* was observed after 20 min of continuous running at anaerobic threshold (Skof and Strojnik 2006). In the present study,  $S_{WU}$  induced the same change in this temperature-related factor than  $R_{WU}$  that is generally thought as more efficient for increasing the muscle temperature. This factor requires further investigation.

Although there are some limits to the information that can be extracted from twitch interpolation results (Taylor et al. 2008a, b) or EMG signals (i.e., amplitude cancellation, cross-talk, impedance; Farina et al. 2004), a good reliability of measurements of VA, PT or M-wave characteristics has been reported in previous studies (Allen et al. 1995; Place et al. 2007). Nevertheless, the lack of change between WU procedures for peripheral measures may be due, at least partially, to a great inter-subject variability and/or the relatively small sample of tested subjects. Further investigation with a larger sample size is required to confirm the results of the present study.

As athletes engaged in a particular discipline use preferentially, but not exclusively, one of the two types of the present WU routines, the effectiveness of these WU regimens cannot be extrapolated because many other parameters are influencing their relationships to athletic performance. In this study,  $R_{WU}$  and  $S_{WU}$  were found equally efficient to improve muscle activation in a group of athletes involved in intermittent activities. However, due to the principle of specificity, it would not make sense to advice distance runners to include only weight-lifting drills in their routines.

In this study, the unchanged electrically evoked isometric MRFD values from pre- to post-WU indicate that the relative importance of possible peripheral factors that affect MRFD such as  $Ca^{2+}$  kinetics, cross-bridge rate and tendon stiffness may be similar between both protocols. If one considers that neural output to the motoneuron is likely to be the major contributor to the ability to achieve steep rise of torque at contraction onset (Grimby et al. 1981), MRFD measured during voluntary contractions may be viewed as more functional. Previous studies have reported that isometric MVC torque is poorly related to dynamic performance (functional movements; Wilson and Murphy 1996). However, MRFD obtained during isometric contraction with electrical stimulation was a good predictor of jump height in elite volley-ball players (De Ruiter et al. 2007). In addition, the rate of knee-extensor torque development during twitch stimulation and voluntary effort have been shown to be moderately but significantly related (Andersen and Aagaard 2005). Hence, one may argue that

measuring electrically evoked isometric MRFD makes sense.

## Conclusion

This study has shown that running- and strength-based warm-up routines induce similar increase in knee extensors force-generating capacity by improving the muscle activation. M-wave and associated twitch characteristics obtained at rest were minimally affected by both treatments. The determination of mechanisms underpinning acute adaptations in neuromuscular system should be expanded to other forms of active warm-up procedures with a particular emphasis on dynamic (e.g., rate of force development magnitude) and functional (e.g., performance measures) parameters. In-line with the above suggestion, future studies might aim at comparing the effect of explosive- and maximal-strength warm-up procedures on neuromuscular function. Determining how to combine the different components of WU (running-, strength- and/or stretching-based procedures) to optimize the post-warm-up responses also warrants further investigation.

## References

- Allen GM, Gandevia SC, McKenzie DK (1995) Reliability of measurements of muscle strength and voluntary activation using twitch interpolation. *Muscle Nerve* 18:593–600. doi:10.1002/mus.880180605
- Andersen LL, Aagaard P (2005) Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *Eur J Appl Physiol* 96:46–52. doi:10.1007/s00421-005-0070-z
- Arsac LM, Locatelli E (2002) Modeling the energetics of 100-m running by using speed curves of world champions. *J Appl Physiol* 92:1781–1788
- Bishop D (2003) Warm-up II. Performance changes following active warm-up and how to structure the warm-up. *Sports Med* 33:483–498. doi:10.2165/00007256-200333070-00002
- Burkett LN, Phillips WT, Ziuraitis J (2005) The best warm-up for the vertical jump in college-age athletic men. *J Strength Cond Res* 19:673–676. doi:10.1519/15204.1
- Candau R, Iorga B, Travers F, Barman T, Lionne C (2003) At physiological temperatures the ATPase rates of shortening soleus and psoas myofibrils are similar. *Biophys J* 85:3132–3141. doi:10.1016/S0006-3495(03)74731-6
- De Ruiter CJ, Vermeulen G, Toussaint HM, De Haan A (2007) Isometric knee extensor torque development and jump height in volleyball players. *Med Sci Sports Exerc* 39:1336–1346. doi:10.1097/mss.0b013e318063c719
- Farina D, Merletti R, Enoka RM (2004) The extraction of neural strategies from the surface EMG. *J Appl Physiol* 96:1486–1495. doi:10.1152/jappphysiol.01070.2003
- Fuglevand AJ, Zackowski KM, Huey KA, Enoka RM (1993) Impairment of neuromuscular propagation during human fatiguing contractions at submaximal forces. *J Physiol* 460:549–572
- Gandevia SC (2001) Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev* 81:1725–1789
- Girard O, Lattier G, Maffiuletti NA, Micallef J-P, Millet GP (2008) Neuromuscular fatigue during a prolonged intermittent exercise: application to tennis. *J Electromyogr Kinesiol* 18:1038–1046. doi:10.1016/j.jelekin.2007.05.005
- Gourgoulis V, Aggeloussis N, Kasimatis P, Mavromatis G, Garas G (2003) Effect of submaximal half-squats warm-up program on vertical jumping ability. *J Strength Cond Res* 17:342–344. doi:10.1519/1533-4287(2003)017<0342:EOASHW>2.0.CO;2
- Grimby L, Hannerz J, Hedman B (1981) The fatigue and voluntary discharge properties of single motor units in man. *J Physiol* 316:545–554
- Güllich A, Schmidtbleicher D (1995) Short-term potentiation of power performance induced by maximal voluntary contractions. In: Hakkinen K, Keskinen KL, Komi P, Mero A (eds) *Book of abstracts—XVth congress of the international society of biomechanics*. ISB, Jyväskylä, pp 348–349
- Hicks A, Fenton J, Garner S, McComas AJ (1989) M wave potentiation during and after muscle activity. *J Appl Physiol* 66:2606–2610
- Holt BW, Lambourne K (2008) The impact of different warm-up protocols on vertical jump performance in male collegiate athletes. *J Strength Cond Res* 22:226–229
- Jones AM, Koppo K, Burnley M (2003) Effects of prior exercise on metabolic and gas exchange responses to exercise. *Sports Med* 33:949–971. doi:10.2165/00007256-200333130-00002
- Koch AJ, O'bryant HS, Stone ME, Sanborn K, Proulx C, Hruby J, Shannonhouse E, Boros R, Stone MH (2003) Effect of warm-up on the standing broad jump in trained and untrained men and women. *J Strength Cond Res* 17:710–714. doi:10.1519/1533-4287(2003)017<0710:EOWOTS>2.0.CO;2
- Kram R, Taylor CR (1990) Energetics of running: a new perspective. *Nature* 346:265–267. doi:10.1038/346265a0
- Kugelberg R, Thornell L-E (1983) Contraction time, histochemical type, and terminal cisternae volume of rat motor units. *Muscle Nerve* 6:149–153. doi:10.1002/mus.880060211
- Magnusson SP, Aagaard P, Larsson B, Kjaer M (2000) Passive energy absorption by human muscle-tendon unit is unaffected by increase in intramuscular temperature. *J Appl Physiol* 88:1215–1220
- McBride JM, Triplett-McBride T, Davie A, Newton RU (2002) The effect of heavy versus light load jump squats on the development of strength, power, and speed. *J Strength Cond Res* 16:75–82. doi:10.1519/1533-4287(2002)016<0075:TEOHVL>2.0.CO;2
- McBride JM, Nimphius S, Erickson TM (2005) The acute effects of heavy-loaded countermovement jumps on sprint performance. *J Strength Cond Res* 19:893–897. doi:10.1519/R-16304.1
- McKenna MJ, Schmidt TA, Hargreaves M, Cameron L, Skinner SL, Kjeldsen K (1993) Sprint training increases human skeletal muscle Na<sup>+</sup>-K<sup>+</sup>-ATPase concentration and improves K<sup>+</sup> regulation. *J Appl Physiol* 75:173–180
- Milner-Brown HS, Stein RB, Lee RG (1975) Synchronization of human motor units: possible roles of exercise and supraspinal reflexes. *Electroencephalogr Clin Neurophysiol* 38:245–254. doi:10.1016/0013-4694(75)90245-X
- Pearce AJ, Kidgell DJ, Zois J, Carlson JS (2009) Effects of secondary warm up following stretching. *Eur J Appl Physiol* 105:175–183
- Place N, Maffiuletti N, Martin A, Lepers R (2007) Assessment of the reliability of central and peripheral fatigue after sustained maximal voluntary contraction of the quadriceps muscle. *Muscle Nerve* 35:486–495. doi:10.1002/mus.20714
- Proske V, Morgan DL, Gregory JE (1993) Thixotropy in skeletal muscle spindles: a review. *Prog Neurobiol* 41:705–721. doi:10.1016/0301-0082(93)90032-N



- Racinais S, Gaoua N, Grantham J (2008) Hyperthermia impairs short-term memory and peripheral motor drive transmission. *J Physiol* 586:4751–4762. doi:[10.1113/jphysiol.2008.157420](https://doi.org/10.1113/jphysiol.2008.157420)
- Radcliffe JC, Radcliffe L (1996) Effects of different warm-up protocols on peak power output during a single response jump task. *Med Sci Sports Exerc* 28:S189. doi:[10.1097/00005768-199605001-01125](https://doi.org/10.1097/00005768-199605001-01125) Abstract
- Ranatunga KW, Sharpe B, Turnbull B (1987) Contractions of a human skeletal muscle at different temperatures. *J Physiol* 390:383–395
- Saez Saez de Villarreal E, Gonzalez-Badillo JJ, Izquierdo M (2007) Optimal warm-up stimuli of muscle activation to enhance short and long-term acute jumping performance. *Eur J Appl Physiol* 100:393–401. doi:[10.1007/s00421-007-0440-9](https://doi.org/10.1007/s00421-007-0440-9)
- Sale DG (2002) Postactivation potentiation: role in human performance. *Exerc Sport Sci Rev* 30:138–143. doi:[10.1097/00003677-200207000-00008](https://doi.org/10.1097/00003677-200207000-00008)
- Skof B, Strojnik V (2006) Neuromuscular fatigue and recovery dynamics following prolonged continuous run at anaerobic threshold. *Br J Sports Med* 40:219–222. doi:[10.1136/bjbm.2005.020966](https://doi.org/10.1136/bjbm.2005.020966)
- Skof B, Strojnik V (2007) The effect of two warm-up protocols on some biomechanical parameters of the neuromuscular system of middle distance runners. *J Strength Cond Res* 21:394–399. doi:[10.1519/R-18055.1](https://doi.org/10.1519/R-18055.1)
- Stewart D, Macaluso A, De Vito G (2003) The effect of an active warm-up on surface EMG and muscle performance in healthy humans. *Eur J Appl Physiol* 89:509–513. doi:[10.1007/s00421-003-0798-2](https://doi.org/10.1007/s00421-003-0798-2)
- Stewart M, Adams R, Alonso A, Van Koesveld B, Campbell S (2007) Warm-up or stretch as preparation for sprint performance? *J Sci Med Sport* 10:403–410. doi:[10.1016/j.jsams.2006.10.001](https://doi.org/10.1016/j.jsams.2006.10.001)
- Taylor KL, Sheppard JM, Lee H, Plummer N (2008a) Negative effect of static stretching restored when combined with a sport specific warm-up component. *J Sci Med Sport*. doi:[10.1016/j.jsams.2008.04.00](https://doi.org/10.1016/j.jsams.2008.04.00)
- Taylor JL, de Haan A, Gerrits KH, de Ruiter CJ (2008b) Point-counterpoint. The interpolated twitch does/does not provide a valid measure of the voluntary activation of muscle. *J Appl Physiol*. doi:[10.1152/jappphysiol.91220.2008](https://doi.org/10.1152/jappphysiol.91220.2008)
- Verkhoshansky Y (1986) Speed-strength preparation and development of strength endurance of athletes in various specializations. *Sov Sports Rev* 21:120–124
- Vetter RE (2007) Effects of six warm-up protocols on sprint and jump performance. *J Strength Cond Res* 21:819–823. doi:[10.1519/R-20296.1](https://doi.org/10.1519/R-20296.1)
- Wilson GJ, Murphy AJ (1996) The use of isometric tests of muscular function in athletic assessment. *Sports Med* 22:19–37. doi:[10.2165/00007256-199622010-00003](https://doi.org/10.2165/00007256-199622010-00003)
- Woods K, Bishop P, Jones E (2007) Warm-up and stretching in the prevention of muscular injury. *Sports Med* 37:1089–1099. doi:[10.2165/00007256-200737120-00006](https://doi.org/10.2165/00007256-200737120-00006)
- Yetter M, Moir GL (2008) The acute effects of heavy back and front squats on speed during forty-meter sprint trials. *J Strength Cond Res* 22:159–165
- Young WB (1993) Training for speed/strength: heavy versus light loads. *Nat Strength Cond J* 15:34–42. doi:[10.1519/0744-0049\(1993\)015<0034:TFSSHV>2.3.CO;2](https://doi.org/10.1519/0744-0049(1993)015<0034:TFSSHV>2.3.CO;2)
- Young WB, Behm D (2003) Effects of running, static stretching and practice jumps on explosive force production and jumping performance. *J Sports Med Phys Fitness* 43:21–27