Warm-up procedures to enhance dynamic muscular performance

Naokazu Miyamoto

Faculty of Sport Sciences, Waseda University, 2-579-15 Mikajima, Tokorozawa, Saitama 359-1192, Japan

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Abstract Warm-up routine prior to sports activities is a customary practice among sporting people and athletes. Although warm-up is done with the expectation that it will enhance subsequent performance, little is known about how one should warm-up. In addition, scientific evidence is lacking on the best procedure that would allow for optimal preparation for a given event, especially for explosive sports activities such as jumping and sprinting. Recently, there has been considerable research on the functional significance of activity-dependent potentiation in dynamic muscular performance. Interest has evolved around whether high-intensity, short-duration muscle contraction as a warm-up procedure can improve such performance, although it remains inconclusive since muscle contractions induce fatigue as well as potentiative effects. In this review, based on evidence from well-controlled studies, proper warm-up procedures for enhancing voluntary dynamic muscular performance are proposed from the perspective of both fatigue and potentiative effects.

Keywords: Postactivation potentiation (PAP), Posttetanic potentiation (PTP), Fatigue, Twitch contraction, Maximal voluntary contraction (MVC), Neuromuscular electrical stimulation (NMES)

Warm-up routine prior to sports activities is a customary practice that most sporting people and athletes perform. Although warm-up is done with the expectation that it will enhance the subsequent performance, little is known about how one should warm-up. In addition, scientific evidence is lacking on the optimal procedure that would allow the proper preparation for a given event, especially for explosive sports activities such as jumping and sprinting. Some of the proposed benefits of warm-up are as follows: increased anaerobic energy provision, greater release of oxygen from hemoglobin and myoglobin, decreased resistance of muscles and joints due to increased muscle temperature, and activity-dependent potentiation1). This review is about the effect of the last factor.

The contractile response of skeletal muscle is affected by its contractile history. The most obvious and well-known effect of contractile history is fatigue, which is the inability of a muscle to generate an expected level of force2,3). Muscle contraction simultaneously induces potentiation. In contrast to fatigue, activity-dependent potentiation is the transient increase in muscle contractile performance following “conditioning” contraction(s)4-6). Thus, it is the balance between these two opposing effects that determines whether subsequent muscular performance is enhanced, diminished, or unchanged. In research on activity-dependent potentiation, postactivation potentiation (PAP) or posttetanic potentiation (PTP) refers to the phenomenon that twitch peak torque is increased after conditioning contraction(s). The difference between PAP and PTP is defined by the nature of the conditioning contraction: PAP is induced after voluntary contraction(s), while PTP is induced after involuntary tetanic contraction(s). For simplicity, in this review, potentiation of twitch peak torque - no matter how induced - is referred to as twitch potentiation (TP). An example of TP is shown in Fig. 1. The most likely mechanism responsible for TP is the myosin regulatory light chain phosphorylation due to prior conditioning contraction7), which leads to individual myosin heads to swing out from the myosin backbone, thereby bringing the actin binding site of the myosin head in closer proximity to the actin filament8). This permits a faster rate of engagement of cross-bridges.
with no change in the rate of dissociation, which would
cause more cross-bridges in the force-generating state
during contraction at a submaximal level of activation (i.e.,
twitch contraction, tetanic contractions at low stimula-
tion frequency, and a few trains at high frequency)9). TP is
much more prominent in muscles with a predominance of
type II (fast twitch) fibers10).

The effect of conditioning contraction volume on the in-
teraction between potentiation and fatigue is highlighted
by several studies. Hamada et al. (2003) used a fatiguing
protocol of sixteen 5 s maximal voluntary isometric con-
tractions (MVCs) of knee extension, with each MVC sep-
arated by a 3 s rest interval11). A twitch response elicited
by stimulating the femoral nerve was assessed pre-MVC,
between each MVC, 1 min after the MVCs, and then ev-
ery 2 min after the MVCs, for 13-min. Twitch peak torque
progressively augmented over the first three MVCs, sug-
gestting that potentiative effect was more predominant
than fatigue when the MVC volume was small. For the
remainder of the fatiguing protocol, however, twitch peak
torque gradually declined, and recorded 32% below the
baseline value by the 16th MVC. This shows that as the
volume of MVCs might continue to increase, the domi-
nance of fatigue also increases. Following the fatiguing
protocol, twitch peak torque gradually increased, and ex-
ceeded the baseline value during the recovery period. This
finding indicates that fatigue dissipated at a faster rate
than the potentiative effect, consequently resulting in TP
during the recovery period. Here, the important key to be
aware of is the question of whether or not a similar effect
would occur during performance of voluntary explosive
activities.

Although the phenomenon of TP and its mechanism(s)
have been investigated for many decades, only recently
attention has been paid to the effects of high-intensity,
short-duration conditioning contraction (i.e., warm-up)
on voluntary muscular performance, and it has remained
controversial whether conditioning contraction(s) for in-
ducing TP can improve sport performance, despite signifi-
cant research in this field12,13). For example, Güllich and
Schmidtbleicher (1996) have shown significant increases
in jump height after 3-5 sets of 5 s isometric MVC of leg
press14). Similarly, Young et al. (1998) have reported that
vertical jump height with additional load was enhanced
after performing a 5 repetitive maximum (RM) half squat
exercise prior to the jump test15). In contrast, Jensen and
Ebben (2003) have failed to find a significant improve-
ment in jump performance after 5 RM squats16). It has
also been reported that there was no significant increase in
vertical jump height after a half or quarter squat exercise
with 90% of 1RM17). A weakness of these studies is that
the presence of TP or the magnitude of myosin regulatory
light chain phosphorylation was not assessed to identify
whether or not, and to what extent, the muscles are in a
potentiated state, and thus it is difficult to associate these
improvements in performance, if any, to activity-depen-
dent potentiation. In addition, one of the factors respon-
sible for these discrepancies could be the recovery time
between the end of the conditioning contraction and the
initiation of the subsequent performance. On this point,
Sale (2002) speculated that a proper interval between the
end of the conditioning contraction and the initiation of
voluntary dynamic performance might be required for
recovery from fatigue by conditioning contraction, in
spite of the decline of potentiative effect with time18).
For example, Gossen and Sale (2000) have shown, even
under the existence of TP, no significant enhancement of
angular velocity or peak power during dynamic knee ex-
tension within 1 min after a 10 s MVC19). In contrast,
with a long recovery interval (7 min) at which time TP would
diminish20,21), Smith and Fry (2007) have shown that, al-
though twitch responses were not assessed, no significant
enhancement of explosive knee extension power was ob-
erved after a 10 s MVC22).

More recently, under well-controlled conditions, it has
been revealed that a conditioning contraction for inducing
TP enhances subsequent dynamic muscular performance
with maximal voluntary effort, such as dynamic joint
torque and power23,24). We have showed that the maximal
voluntary isokinetic eccentric torque of plantar flexion
was significantly enhanced 1 to 3 min after a 6 s MVC
(+8%), while it remained unchanged when the condi-
tioning MVC was not performed25). These observations
indicate that a high-intensity, short-duration muscle con-
traction can enhance subsequent voluntary dynamic mus-
cular performance within a proper recovery interval, and
support the Sale’s hypothesis that activity-dependent po-
tentiation can also occur in sports activities with maximal
voluntary effort18). However, it is noteworthy that the po-
tentiation of voluntary muscular performance in the pre-
vious studies failed to occur immediately after the condi-
tioning MVC, despite the occurrence of maximal TP23,24).
The previous study showed that the electromyographic
(EMG) activities of agonist muscles were decreased im-
mEDIATELY after the conditioning contraction, despite no
significant changes in the M-wave amplitude26). These re-
Sults strongly suggest that the dissociation in potentiation
immediately after the conditioning contraction between
twitch torque and voluntary dynamic muscular perform-
ance was attributed to central fatigue occurring during
the conditioning contraction and that consequently it
could attenuate the enhancement of subsequent voluntary
dynamic muscular performance. Thus, it is assumed that
reducing central fatigue (as well as peripheral fatigue)
occurring during conditioning contraction while keeping
greater potentiative effects can result in more immediate,
greater enhancement of explosive muscular performance.

One approach to prevent or minimize central fatigue
that occurs during high-intensity conditioning contraction
is to shorten its duration. In addition, the difference in
duration of high-intensity conditioning contraction could
be a factor responsible for the inconsistent results of the
studies on whether conditioning contractions for induc-
ing TP improved sport performance. Most recently, we
have examined the effect of the duration of high-intensity
conditioning contraction on subsequent muscular perfor-
manence. Maximal voluntary concentric torque of knee
extension was significantly enhanced (+7%) at 1 and 3
min after a 5 s isometric MVC, but not immediately af-
fter the conditioning MVC. On the other hand, after a 3 s
MVC, although smaller TP was observed compared with
5 s MVC trial, the maximal voluntary concentric torque
did not significantly change at any time point. In 10 s
MVC trial, the maximal voluntary dynamic torque signifi-
cantly decreased immediately and 1 min after the condi-
tioning MVC (−7% and −4%, respectively) and returned
to the baseline at 3 and 5 min after the MVC.

Another possible approach to prevent or minimize
central fatigue that occurs during high-intensity, short-
duration conditioning contraction is the use of percu-
taneous neuromuscular electrical stimulation (NMES)
as a conditioning contraction, because NMES bypasses
volition for muscle contraction. After examining the ef-
fects of intensity, stimulation frequency, and duration of
NMES on the extent of TP of the quadriceps femoris4,6,25),
we determined the optimal NMES protocol for producing
greater TP with less fatigue. Then, we used 20 Hz NMES
for 5 s at ~60% MVC level as a conditioning contrac-

tion where almost all muscle fibers of the knee extensor
muscles would be recruited, and showed that the maximal
voluntary concentric torque and power were significantly
increased not only 1 and 3 min after (+8%) but also im-
mediately after the conditioning contraction (+5%)25).
These results suggest that an approximately 5 s of condi-
tioning contractions, performed with isometric MVC or
20-Hz NMES with high intensity, can be a modality to
enhance voluntary dynamic muscular performance, with
the latter having more immediate effect.

As mentioned above, the mechanism for activity-de-
pendent potentiation is a larger number of cross-bridges
in the force-generating state during contraction, due to
phosphorylation of the regulatory light chain of myosin8).
Considering that maximal effort contraction will be of
relatively high firing frequency and that potentiation is
less evident under this condition, it becomes difficult to
accept that high-intensity conditioning contraction could
enhance voluntary dynamic muscular performance with
maximal efforts. Indeed, until recently, it has been gener-
ally accepted that this plays out nicely for submaximal
contractions, but plays almost no role in Ca2+ saturated
conditions such as maximal contraction evoked with high
stimulation frequency. Thus, isometric MVC torque can-
not increase after a conditioning contraction8,26,27). Ne-
evertheless, recent studies have shown that explosive muscu-
lar performances with maximal efforts were potentiated
after a brief conditioning contraction23-25). This could be
because the activation level (i.e., firing frequency) of the
muscle fibers recruited during the maximal voluntary dy-
namic contractions is actually submaximal, especially for
fast (i.e., high shortening velocity) movement; whereas
the activation level during isometric MVC is almost "truly
maximal"25).

In summary, in exploiting high-intensity conditioning
contraction for inducing TP to enhance explosive mus-
cular performance, two dilemmas should be considered.
First, a more prolonged conditioning contraction activates
the activity-dependent potentiation mechanism (i.e., phos-
phorylation of myosin regulatory light chain, especially in
type II fiber) to a greater extent; but also produces greater
fatigue (Fig. 2). The second dilemma is that the longer
the recovery period between the end of the conditioning
contraction and the initiation of performance, the greater
the recovery from fatigue, but also the greater the decay
of the potentiative effect (Fig. 2). It is suggested that an
approximately 5 s conditioning contraction performed
with isometric MVC or a set of a few repetitions with
heavy weight can be a modality to enhance dynamic vol-
untary joint performance and that short (≤ 3 s) and long
(≥ 10 s) duration MVC cannot be a proper stimulus for
enhancing dynamic performance with maximal voluntary
effort.

**Fig. 2** A modified model of the hypothetical relationship between potentiative effect (dotted line) and fatigue (dashed line) during high-intensity conditioning contrac-
tion and after the optimal conditioning contraction (re-
covery time), based on recent data23-25). During voluntary
conditioning contraction, both potentiative effect and fa-
tigue increase when conditioning contraction volume is
low. As the volume increases, potentiative effect reaches
the plateau whereas fatigue continues to increase. There-
fore, the optimal volume of conditioning contraction is
determined by the balance between these two opposing
effects. During recovery time following the optimal con-
ditioning contraction, fatigue dissipates at a faster rate
compared with potentiative effect, and consequently ex-
plosive sports performance can be enhanced after proper
recovery interval (thick black line). When conditioning
contraction is performed through percutaneous neuro-
muscular electrical stimulation (NMES), the occurrence
of central fatigue is minimized, and consequently the
magnitude of fatigue during conditioning contraction is
reduced (dashed gray line). Thus, the enhancement of
explosive muscular performance is observed at earlier
recovery phase (thick gray line).
From a practical viewpoint, the author recommends including high-intensity, short-duration muscle contraction during warm-up procedures for explosive sports activities. Namely, although submaximal contractions have so far been used as warm-up procedures in order to reduce fatigue, the recent findings indicate that high-intensity, short-duration contractions can be a more effective warm-up modality for high-power activities. In addition, the use of NMES, with proper duration, intensity and stimulation frequency, can be recommended as a more immediately effective warm-up modality. Furthermore, it may be possible to explain the effectiveness of complex training, which has been defined as combining plyometric and weight-resistance exercises in the same training session, for the purpose of acute improvement of muscular performance. Lastly, the author hopes that this review provides valuable scientific evidence and can contribute towards future research efforts for establishing optimal warm-up procedures for explosive sports activities.

References