Comparing muscle temperature during static and dynamic squatting with and without whole-body vibration

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Summary
The aim of this study was to investigate the influence of shallow dynamic squatting (DS) versus static squatting (SS) with or without concurrent side-to-side alternating whole-body vibration (WBV) on vastus lateralis temperature and cardiovascular stress as indicated by heart rate (HR). Ten participants (five men, five women) participated in four interventions [DS with WBV (DS⁺), DS without WBV (DS⁻), SS with WBV (SS⁺), SS without WBV (SS⁻)] 48 h apart, in a randomized order. The interventions were preceded by about 20-min rest period, consisted of 10 mins with or without WBV (26 or 0 Hz) with SS (40° of knee flexion) or DS (55° of knee flexion, at a cadence of 50 bpm) where SS⁺ and DS⁻ were metabolically matched. Muscle (Tem), core (Tc), skin temperature (Tsk), HR and VO₂ were recorded during each intervention. For Tem, there was a time (P<0.01) and WBV (P<0.01) effect but no squat effect was evident, and there was time xWBV interaction effect (P<0.01). In all four interventions, the work load was too low to cause cardiovascular stress. Instead normal, moderate physiological effects of exercise on autonomic control were observed as indicated by HR; there were no significant increases in Tsk or Tc. There appears to be no benefit in performing an unloaded, shallow DS⁺ at a tempo of 50 bpm as Tem, HR, VO₂ are likely to be increased by the same amount and rate without WBV. However, combining SS with WBV could be advantageous to rapidly increasing soft tissue temperature prior to performing rehabilitation exercises when dynamic exercise cannot be performed.

Introduction
Acute whole-body vibration (WBV) has been reported to increase muscular power (Cochrane & Stannard, 2005), strength (Torvinen et al., 2002), peripheral circulation (Lohman et al., 2007) and muscle blood flow (Kerschan-Schinfl et al., 2001). The rapid and repetitive eccentric/concentric action of WBV evokes muscular work (Rittweger et al., 2001), elevates metabolic rate (Rittweger et al., 2000) and elicits mild cardiovascular changes (Cochrane et al., 2008a) similar to those of moderate walking (Rittweger et al., 2001). These physiological responses are normally associated with an increase in muscle temperature, which is central to optimal muscle function (Bennett, 1984), injury prevention (Bixler & Jones, 1992) and exercise-associated rehabilitation (Rimington et al., 1994).

The oscillating action of the WBV platform is thought to elicit rapid, reflex-mediated stretch-shortening of the distal supporting (calf and thigh) muscles with associated rapid-cycling eccentric/concentric contractions (Rittweger et al., 2001, 2003; Cardinale & Bosco, 2003). It is well known that eccentric muscle work acts like a brake by absorbing external mechanical energy and results in local heat production (Constable et al., 1997). On the other hand, concentric muscle contraction acts like a motor to convert chemical energy into mechanical work and local heat production ensues primarily as a by-product of metabolism, although to a lesser extent during concentric than eccentric work (Curtin & Woledge, 1978). We have previously shown that concentric exercise (cycling) produces less heat than WBV for the same metabolic rate (VO₂) (Cochrane et al., 2008b), probably because little external work is absorbed during concentric exercise.

Enjoying popularity as an alternative exercise modality, WBV is currently being prescribed by trainers, coaches and exercise therapists on the basis that it may provide a neurogenic potentiation to the muscle, which cannot be achieved by other traditional exercises. Previous work has found that matched for...
metabolic rate, the rate of muscle temperature doubled when acute WBV was superimposed upon gentle, slow dynamic squatting (DS) compared to stationary cycling (Cochrane et al., 2008b). However, the aforementioned study did not distinguish between the effects of the vibration and squatting on the increase in muscle temperature. Static squatting (SS) and DS are common exercises utilized in WBV training (Rittweger et al., 2001; Cardinale & Lim, 2003; Ronnestad, 2004; Roelants et al., 2006; Abercromby et al., 2007a; Cochrane et al., 2008b), but it is unknown if SS or DS is superior in increasing muscle temperature. It is crucial to understanding the physiological responses involved in the application of WBV. It may assist to provide guidance to two reasons for which WBV is commonly employed. It is reasonable, therefore, to propose that the responses of muscle vibration and different types of squatting on muscle temperature and cardiovascular stress as indicated by HR. It was hypothesized that when DS was superimposed upon WBV, muscle temperature, HR, and VO$_2$ would exceed both DS alone and SS with WBV.

Methods

Participants

Five men [(mean ± SD) age 31.4 ± 5.2 year; body mass 79.9 ± 10.9 kg, height 1.76 ± 0.1 m] and five women (28.1 ± 5.8 year; body mass 63.7 ± 5.8 kg, height 1.67 ± 0.1 m), with an active lifestyle of undertaking routine physical activity at least three times a week volunteered to participate in the study. Written informed consent was obtained from the participants, and ethical approval was granted by the local University Human Ethics Committee.

Study design

Every participant performed four interventions, in a randomized order with 48 h separating each testing session. The interventions were preceded by a ~20-min rest period followed by 10 mins with a SS (40° knee angle) or DS (55° knee angle, cadence 50 bpm) with or without WBV (26 or 0 Hz), with the four interventions being DS with WBV (DS+), DS without WBV (DS−), SS with WBV (SS+) and SS without WBV (SS−). For the rest phase, the participants sat quietly on an adjustable reclined examination table. We selected 40° knee flexion for SS and 55° knee flexion for DS, the angle being in the lower half of those used in past studies in which SS and DS with WBV were typically performed at knee flexion angles of 20–70° (Cardinale & Lim, 2003; Cormie et al., 2006; Roelants et al., 2006; Abercromby et al., 2007a) (erect stance = 0° knee flexion) and between 35 and 90° (Rittweger et al., 2001; Abercromby et al., 2007a; Cochrane et al., 2008b), respectively. Additionally, the metabolic rate needed to be matched and from our pilot testing DS— at 50 bpm and 55° of knee flexion was identical to the metabolic rate of a SS+ held at 40° of knee flexion when performed at 26 Hz and 40° of knee flexion. Hence, for our study, we selected 40° knee flexion for SS and 55° knee flexion for DS.

Participants were fully familiarized with equipment and protocols before undertaking their first session. Lastly, all interventions were performed at a constant ambient temperature [20.3 ± 0.6°C (SE)] and relative humidity [47.5 ± 2% (SE)].

Physiological measures

Measuring muscle temperature ($T_m$) involved sterilizing the insertion area of vastus lateralis muscle with betadine antiseptic solution (Faulding HealthCare, QLD, Australia). The muscle was then anesthetized to a maximum depth of ~38 mm by infiltrating 5 ml of 2% xylocaine (Astra Zeneca, Australia), using a 25 gauge, 0.5 × 38 mm, needle (BD, Singapore). A 16-gauge, 1.2 × 45-mm cannula (BD, Venflon, Sweden), was inserted at an inclination of ~45° into the vastus lateralis at a site two-thirds the way along a line joining the anterior superior iliac spine and the proximal aspect of the patella with the leg extended (femoro-tibial angle = 0°). To ensure that subsequent thermocouple placement was consistent between interventions, the insertion site was marked with a permanent pen, measured and recorded.

The needle of the cannula stylet was then withdrawn, and a flexible sensor muscle thermocouple (Model IT-17:3 Type T stranded thermocouple wire; Physitemp Instruments Inc, Clifton, NJ, USA) was inserted into the cannula to a depth of 45 mm. To prevent any dislodgement, a sterile dressing (Tegaderm I.V., 3M Health Care, Neuss, Germany) and surgical tape (Transpore, 3M, Neuss, Germany) were used to secure the catheter shaft and the thermocouple to the leg. To ensure that the thermocouple remained at the same depth during each session, a permanent pen was used to mark the entry of the thermistor into the cannula, which was constantly monitored by the researcher for any displacement. The thermocouple was connected to an electronic display unit (TH-8 Thermalert; Physitemp Instruments Inc). $T_m$ was monitored every 5 min during the rest phase, and during the interventions, $T_m$ was recorded every minute from 0 ($T_0$) to 10 min ($T_{10}$).

Using an infrared thermometer (First Temp Genius; Sherwood, Davis & Geck, St Louis, MO, USA), skin temperature ($T_a$) was measured at four sites: the right shin, anterior thigh, shoulder and chest, and mean $T_a$ was calculated using the four site weighted method of Ramanathan (1964).
Whole-body vibration and squatting interventions

WBV was performed on a commercial machine (Galileo Sport, Novotec, Pforzheim, Germany), which has a teeter board that produces side-to-side alternating vertical sinusoidal vibration to the body. To negate the possibility of discomfort to the sole of the foot and to standardize the vibration dampening caused by footwear, participants wore the same sport shoes for all interventions and placed their feet at a fixed distance marked on the plate either side of the central axis which corresponded to a vibration amplitude (peak-to-peak) of 6 mm. Vibration frequency was either 26 or 0 Hz (peak-to-peak amplitude 0 mm) for both SS (knee angle 40°) or DS (knee angle 55°). For SS and DS, a manual goniometer was used to set the knee angle and an adjustable hurdle was placed under the gluteal fold. For temporal control during DS, a metronome was set at 50 bpm and the participants were instructed to maintain a continuous and smooth squatting motion.

Statistical analyses

The change in $T_m$ was calculated from each interval between $T_6$ and $T_{10}$ and averaged to obtain the intervention mean for the 10 participants. $T_c$ and mean $T_{rk}$ were averaged at 0 and 10 min, and for HR and VO$_2$, the final 2 min (8–10 mins) were averaged. A three-factor repeated measures [time × squat (dynamic and static) × WBV (with WBV and without WBV)] ANOVA was performed to test variation in $T_m$, $T_c$, mean $T_{rk}$ and HR. A two-factor repeated measures (squat × WBV) ANOVA was used to analyse $\Delta T_m$, $\Delta$ HR, $\Delta$ Mean $T_{rk}$, $\Delta$ T$_{rk}$, and VO$_2$. For multiple comparisons significance, post hoc pairwise comparisons were performed and adjusted to Bonferroni’s rule. All statistical analyses were performed using statistical software SAS for Windows Version 16 (Chicago, IL, USA), and statistical significance was set at $P<0.05$.

Results

There was no difference in VO$_2$ between SS+ and DS− nor was there a difference in VO$_2$ between DS+ and DS− and SS+ (Table 1). DS was associated with higher ($P<0.01$) VO$_2$ than was SS, VO$_2$ was higher ($P<0.01$) during WBV than without WBV, but there was no significant squat × WBV interaction effect for VO$_2$.

Following a rest period of 20 min, there was no significant difference in starting (0 min) $T_m$ ($P = 0.77$) between the four interventions (Table 1). $T_m$ increased with time ($P<0.01$) and with WBV ($P<0.01$) but there was no difference in elevated $T_m$ between the two types of squat ($P = 0.06$). There was a time × squat interaction effect where DS and SS were associated with increased ($P<0.01$) $T_m$ with time (Fig. 1a). Likewise, there was time × WBV interaction effect ($P<0.01$), showing that with WBV $T_m$ increased with time to a greater extent than without WBV (Fig. 1b). Also there was a WBV × squat × time interaction effect ($P<0.01$), and Fig. 1c shows the time course of $T_m$ for DS+, DS−, SS+ and SS−. Finally, for $\Delta T_m$, there was a squat and WBV effect but no significance was detected between the interventions (Table 1).

There was no significant difference in HR$_0$ ($P = 0.43$) between the interventions (Table 1). A time × WBV interaction effect was found where HR was higher at 10 mins with WBV compared to without WBV. For mean $T_{rk}$, there was no significant difference ($P = 0.62$) between the interventions and there were no significant time interaction effect. The change in thigh $T_{rk}$ was significantly higher in SS+ compared to SS−, DS+ and DS− but there were no other differences (Table 1). There were no significant differences in core temperature between the interventions (Table 1) and no time interaction effects.

Discussion

The primary aim of this study was to compare the $T_m$ and HR responses to SS+ and DS− when matched for metabolic rate. There were no significant differences in $T_m$, HR and VO$_2$, thereby confirming the hypothesis that when matched for metabolic rate, $T_m$ and HR responses are similar when comparing shallow DS and SS with concurrent WBV. This suggests that the type of squat performed (DS or SS) with or without WBV will independently increase $T_m$.

Our second hypothesis that DS+ at 50 bpm (55° knee flexion) would increase $T_m$ significantly more than DS− and SS+ was not sustained, as the addition of WBV to DS+ did not significantly elevate $T_m$ (Fig. 1c). The expectation has been that when muscles are stretched more, the vibration effect on muscle activation will be greater, because of an increased sensitivity of the muscle spindles during the stretch (Roelants et al., 2006; Kemertzis et al., 2008). Furthermore, during a DS, the lowering phase should elicit a larger knee angle and produce a greater muscle stretch and increase Ia-afferent stimulation and augment muscle activation (Abercromby et al., 2007a). With an increase in muscle activation from WBV, a greater energy expenditure and greater rise of $T_m$ would be expected, but this
Table 1  Group mean (±SE) oxygen uptake, mean skin temperature, core temperature and heart rate associated with combinations of dynamic and static squatting with and without whole-body vibration.

<table>
<thead>
<tr>
<th>Variable</th>
<th>DS+</th>
<th>DS−</th>
<th>SS+</th>
<th>SS−</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO2 (ml kg⁻¹ min⁻¹)</td>
<td>13 ± 1.2 ¹</td>
<td>10 ± 0.8 ¹</td>
<td>11 ± 1.2 ¹</td>
<td>7 ± 1.1</td>
</tr>
<tr>
<td>Tm 0 (°C)</td>
<td>35.6 ± 0.3</td>
<td>35.9 ± 0.3</td>
<td>35.8 ± 0.2</td>
<td>35.5 ± 0.3</td>
</tr>
<tr>
<td>Tm 10 (°C)</td>
<td>37.2 ± 0.3 ¹</td>
<td>37.0 ± 0.3 ¹</td>
<td>37.2 ± 0.2 ⁹</td>
<td>36.3 ± 0.3 ⁹</td>
</tr>
<tr>
<td>Δ Tn (°C)</td>
<td>1.6 ± 0.2</td>
<td>1.1 ± 0.1</td>
<td>1.4 ± 0.1</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>HR 0 (bpm)</td>
<td>74.7 ± 4.8</td>
<td>72.1 ± 3.0</td>
<td>77.2 ± 2.7</td>
<td>69.9 ± 5.8</td>
</tr>
<tr>
<td>HR 10 (bpm)</td>
<td>110.6 ± 6.5</td>
<td>89.0 ± 5.4 ²</td>
<td>113.5 ± 4.1 ²</td>
<td>91.6 ± 5.8 ²</td>
</tr>
<tr>
<td>Δ HR (bpm)</td>
<td>13.6 ± 9.9</td>
<td>13.9 ± 5.5</td>
<td>36.3 ± 11.0</td>
<td>21.2 ± 6.9</td>
</tr>
<tr>
<td>Tc 0 (°C)</td>
<td>37.2 ± 0.1</td>
<td>37.2 ± 0.1</td>
<td>37.2 ± 0.1</td>
<td>37.2 ± 0.1</td>
</tr>
<tr>
<td>Tc 10 (°C)</td>
<td>37.3 ± 0.1</td>
<td>37.3 ± 0.1</td>
<td>37.2 ± 0.1</td>
<td>37.2 ± 0.1</td>
</tr>
<tr>
<td>Δ Tc (°C)</td>
<td>0.1 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.1 ± 0.0</td>
</tr>
<tr>
<td>Mean Tia 0 (°C)</td>
<td>31.4 ± 0.4</td>
<td>31.5 ± 0.3</td>
<td>30.9 ± 0.4</td>
<td>31.1 ± 0.4</td>
</tr>
<tr>
<td>Mean Tia 10 (°C)</td>
<td>31.6 ± 0.5</td>
<td>31.7 ± 0.4</td>
<td>31.7 ± 0.5</td>
<td>31.0 ± 0.4</td>
</tr>
<tr>
<td>Δ Mean Tia (°C)</td>
<td>0.2 ± 0.2</td>
<td>0.2 ± 0.2</td>
<td>0.8 ± 0.3</td>
<td>~0.1 ± 0.2</td>
</tr>
<tr>
<td>Tia.0 (°C)</td>
<td>29.1 ± 0.5</td>
<td>29.5 ± 0.5</td>
<td>28.7 ± 0.6</td>
<td>28.6 ± 0.8</td>
</tr>
<tr>
<td>Tia.10 (°C)</td>
<td>29.9 ± 0.8</td>
<td>29.7 ± 0.5</td>
<td>31.0 ± 0.8 ²</td>
<td>29.4 ± 0.4</td>
</tr>
<tr>
<td>Δ Tia.0 (°C)</td>
<td>0.8 ± 0.4</td>
<td>0.2 ± 0.2</td>
<td>2.3 ± 0.2  ²</td>
<td>0.8 ± 0.2</td>
</tr>
</tbody>
</table>

DS+, Dynamic Squat with WBV; DS−, Dynamic Squat without WBV; SS+, Static Squat with WBV; SS−, Static Squat without WBV. VO2, Rate of oxygen uptake values averaged over 8–10 min; Tm 0, muscle temperature at 0 min; Tm 10, muscle temperature at 10 min; Δ Tn, change in muscle temperature; HR 0, heart rate at 0 min; HR 10, mean heart rate between 8 and 10 min; Δ HR, change in heart rate; Tc 0, core temperature at 0 min; Tc 10, core temperature at 10 min; Δ Tc, change in core temp; Mean Tia 0, mean skin temperature at 0 min; Mean Tia 10, mean skin temperature at 10 min; Δ Mean Tia, change in skin temp; Tia.0, skin thigh temperature at 0 min; Tia.10, skin thigh temperature at 10 min; Δ Tia.0, change in skin thigh temperature.

¹P<0.01 compared to Tm 0.
²P<0.05 compared to SS−.
³P<0.01 compared to HR 0.
⁴P<0.05 compared to DS+, DS−, SS−.

The current proposed mechanism of WBV is based around a neurogenic potentiation involving spinal reflexes and muscle activation (Cardinale & Bosco, 2003; Rittweger et al., 2003). Given that DS is a multi-joint technique that involves a complex movement, motor and sensory patterns, DS may have altered the magnitude of the reflex response and/or the intrasural fibre tension and Ia sensitivity during the concentric and eccentric phases of DS (Abercromby et al., 2007a), which in turn would evoke less muscular work and a lower metabolic rate. Damping of vibration results in mechanical energy and muscle activation (Wakeling et al., 2002) which is dependent on joint angle and muscle force and tension (Wakeling & Nigg, 2001). It has been shown that during WBV, head acceleration decreases when DS occurs from 10 to 30° of knee flexion but increases when performed at 31–35°, suggesting that the ability of the lower limbs to damp vibration is less effective as flexion angle increases (Abercromby et al., 2007b). It is plausible that during DS+, there is an optimal knee angle range which damps the vibration to enhance muscle activation. In the current study, DS was performed at 55°; thus, for 45% of the duration of each DS cycle, the knee flexion angle was >30°, which may in part have suppressed the damping response compared to that associated with SS+. Therefore, it may be more favourable if static or single joint exercises are performed with vibration, because the full potential of the neurogenic response during WBV is more likely to be realized.

There was an interesting observation that after the first minute of DS+ and SS+, Tm increased by 0.4 and 0.3°C, respectively, compared to 0°C for DS− and SS− (Fig. 1b). It is possible that the rapid and significant rise in Tm might be a result of vibration causing mechanical energy to be absorbed by the muscle (Ettema & Huijing, 1994), especially as there may be a short interval before the muscles accommodate or adapt to the acute imposition of vibration. Another possible explanation for this rapid rise in Tm is that WBV may have caused venous dilatation of the thigh muscle, as it has been previously
reported that strenuous dynamic knee-exercise increases thigh $T_m$, venous blood temperature and venous blood flow (Gonzalez-Alonso et al., 2000). Therefore, the rapid increase in $T_m$ may be owing to some effect of WBV exercise or because the dynamic exercise was less strenuous (as shown by the slow $T_m$ rise in DS−).

The level of cardiovascular stress in DS+ was not greater than that in DS− and SS+. However, HR increased significantly with time, with HR higher at 10 min with WBV than without WBV. This indicates that muscular work above isometric took place and supports earlier studies indicating that acute WBV does elicit very mild cardiovascular changes (Rittweger et al., 2000; Cochrane et al., 2008a; Lythgo et al., 2009). $T_m$ never increased above $T_c$; therefore, various sources of heat could have increased $T_m$, such as an increase in muscle perfusion causing muscle to heat with warmer blood from the core; the conversion of mechanical energy to heat; or an increase in muscle ATP turnover. The increases in HR of the four interventions do not sufficiently indicate an increase in thigh muscle perfusion. However, $T_{sk}$ at the thigh may provide some indication about the heat transport in thigh muscle was altered by perfusion. In our study, $T_{sk}$ was greater in SS compared to DS where SS+ exhibited a greater increase compared to SS−. Therefore, the static posture with vibration may have changed muscle perfusion by increasing heat transport. Given the specific heat of muscle at 37–5°C is 3590 J kg$^{-1}$ °C$^{-1}$ (Gonzalez-Alonso et al., 2000) and skeletal muscle mass of the lower limb is approximately 16 kg (Shih et al., 2000), then an estimated 80 kJ would have been required to raise $T_m$ by 1–4°C during SS+. However, Zange et al. (2009) found that during 3-min isometric ankle plantarflexion, ATP consumption did not change with either vibration (f = 20 Hz, amplitude = 2 mm) or without vibration. But when both arterial occlusion and vibration were applied ATP consumption increased significantly, signifying the importance of muscle perfusion in vibration exercise.

During WBV in the current study, there were several observations of skin erythema, with some participants also experiencing temporary itching, which is an innocuous side effect that normally coincides with a rise in $T_{sk}$ (Oliveri et al., 1989) and subsides after some minutes of WBV (Rittweger et al., 2000; Hazell et al., 2008). However, in our current study, there were no significant changes in mean $T_{sk}$ between the four interventions, which differs from previous reports that vibration increases $T_{sk}$ (Oliveri et al., 1989; Hazell et al., 2008). The
discrepancy is because of the differences in vibration regimen. For instance, Oliveri et al. (1989) administered localized vibration (50 Hz) whilst Hazell et al. (2008) utilized an intermittent protocol of 15 mins at 45 Hz, which differs greatly from the current experimental protocol of 10 min continuous at 26 Hz. The moderate but significant change in $T_m$ reflected the low level of exercise intensity sustained in the current interventions and explains why there were no significant effects on $T_c$. This was not unexpected given that a higher metabolic rate would be required to generate enough heat to raise $T_m$ beyond that of $T_c$ (Sargeant, 1987).

From the results of this study, there appears to be no benefit in performing an unloaded, shallow DS+ at a tempo of 50 bpm, as $T_m$, HR and VO$_2$ are likely to be increased by the same amount and rate without WBV. However, the application of SS+ has advantages in sport performance when re-warming athletes after interval breaks, as it would incur a low metabolic cost and be time efficient. Likewise, SS+ may increase soft tissue amount and rate without WBV. However, the application of SS+ may be influenced by a postural control mechanism and/or a damping response (Abercromby et al., 2007a).

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