

WHOLE BODY VIBRATION AND ATHLETIC PERFORMANCE: A SCOPING REVIEW

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ABSTRACT

Over the past 30 years, whole body vibration (WBV) has received much attention in research, therapeutics, and athletics as a means to restore or improve motor function and athletic performance. The purpose of this review was to determine if WBV could increase athletic performance in competitive and/or elite athletes. As reported in 19 studies, WBV (36.1 Hz, 3.1 mm) had an overall 2.5% acute effect on MVC force (-2.1%), power (3.1%), flexibility (9.2%), and athletic performance (-0.2%) in 379 (172 male, 207 female) athletes representing 11 sports. Only nine or 33% of the 27 comparisons between WBV and active controls were statistically significant. There were three comparisons, suggesting unfavorable effects of WBV on performance. In 15 studies, WBV (32.1 Hz, 4.6 mm) had an overall 10.3% chronic effect on MVC force (14.4%), power (9.1%), flexibility (16.5%), and athletic performance (1.1%) in 303 (81 male, 222 female) athletes, representing eight sports. Nine or 55% of the 19 comparisons between WBV and active control were statistically significant. Taken all of the data from the 34 studies, WBV increased acute and chronic performance by 6.4% in 682 (253 males, 429 female) athletes, representing 14 sports. However, only 18 or 44% of the 46 comparisons between WBV vs. active control were statistically significant. Strictly speaking of 'athletic performance', the acute and chronic WBV-effect, respectively, was -0.3% and 1.1%. In conclusion, the present scoping review found little and inconsistent evidence that acute and chronic WBV would improve athletic performance in competitive and/or elite athletes.

Key Words: exercise, muscle, athletes, wbv

RESUMEN

La vibración total del cuerpo (WBV) ha recibido una gran atención en el ámbito del deporte. El objetivo de esta revisión es determinar si la WBV puede mejorar el rendimiento deportivo en deportistas de élite. Los resultados de 19 estudios indican que WBV (36.1 Hz, 2.1 mm) tiene un efecto total agudo de un 2.5%, en la máxima contracción voluntaria (-2.1%), potencia (3.1%), flexibilidad (9.2%), y rendimiento deportivo (-0.2%). En 15 estudios, que engloban a un total de 303 deportistas, WBV (32.1 Hz, 4.6 mm) tiene un efecto total crónico de un 10.3%, en la máxima contracción voluntaria (14.4%), potencia (9.1%), flexibilidad (16.5%), y rendimiento deportivo (1.1%). Atendiendo al total de resultados de los 34 estudios, con 682 deportistas, el WBV incrementaba el rendimiento agudo y crónico en un 6.4%. Sin embargo, únicamente 18 o 44% de las 46 comparaciones entre WBV vs. controles eran estadísticamente significativas. Estrictamente hablando de "rendimiento deportivo", el efecto agudo y crónico de la WBV era, respectivamente, de -0.3% y 1.1%. En conclusión, la presente revisión encuentra poca e inconsistente evidencia de que el uso agudo y crónico de la WBV pueda incrementar el rendimiento deportivo en deportistas de competición y/o de élite.

Palabras clave: ejercicio, músculo, deportistas, wbv

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INTRODUCTION

Other than physical activity and exercise itself, there is perhaps no other non-pharmaceutical therapeutical intervention modality that has been used so frequently in as many populations than mechanical vibration, delivered especially in the form of whole body mechanical vibration (WBV). A recent PubMed search using 'WBV' and the MeSH term, 'vibration' as search words, resulted in 509 hits, including 51 reviews, a few of them sampled here (Brooke-Wavell & Mansfield, 2009; Cardinale & Bosco, 2003; Cochrane, 2011, 2012; Costantino, Gimigliano, Olvirri, & Gimigliano, 2014; Issurin, 2005; Jordan, Norris, Smith, & Herzog, 2005; Lam, Lau, Chung, & Pang, 2012; Lau, et al., 2011; Lindberg & Carlsson, 2012; Luo, McNamara, & Moran, 2005; Merriman & Jackson, 2009; Nordlund & Thorstensson, 2007; Rauch, et al., 2010; Rittweger, 2010; Totosy de Zepetnek, Giangregorio, & Craven, 2009; Wilcock, Whatman, Harris, & Keogh, 2009). WBV as therapy has been applied in a range of conditions and patients who suffered from: osteoporosis (Torvinen, et al., 2003; Turner, et al., 2011), obesity (Milanese, et al., 2013), type II diabetes (Baum, Votteler, & Schiab, 2007), age-related reductions in gait speed and walking ability (Lindberg & Carlsson, 2012), knee osteoarthritis (Park, et al., 2013), joint replacements (Johnson, et al., 2010), frailty (Sitja-Rabert, et al., 2011; Zhang, et al., 2014), age-related sarcopenia (Bogaerts, et al., 2007), age-related loss of muscle power (Osugi, Iwamoto, Yamazaki, & Takakuwa, 2014), ankle and knee instability (Melnik, Kofler, Faist, Hodapp, & Gollhofer, 2008; Melnik, Schloz, Schmitt, & Gollhofer, 2009), impaired knee proprioception and postural stability after anterior cruciate ligament reconstruction (Moezy, Olyaei, Hadian, Razi, & Faghihzadeh, 2008), low back pain (Lings & Leboeuf-Yde, 2000; Perraton, Machotka, & Kumar, 2011), bed rest (Trudel, et al., 2012), fibromyalgia (Alentorn-Geli, Padilla, Moras, Lazaro Haro, & Fernandez-Sola, 2008), neurodegenerative diseases (Sitja Rabert, et al., 2012), Parkinson's disease (Arias, Chouza, Vivas, & Cudeiro, 2009), multiple sclerosis (Jackson, Merriman, Vanderburgh, & Brahler, 2008; Sitja Rabert, et al., 2012), stroke (Tihanyi, Horváth, Fazekas, Hortobágyi, & Tihanyi, 2007), post-polio syndrome (Brogardh, Flansbjerg, & Lexell, 2010), spinal cord injury (Alizadeh-Meghrizi, Masani, Popovic, & Craven, 2012; Sayenko, Masani, Alizadeh-Meghrizi, Popovic, & Craven, 2010), cerebral palsy (Ahlborg, Andersson, & Julin, 2006), gastric mobility dysfunction (Miyazaki, 2000), attention deficit disorder (Fuermaier, et al., 2014), and cognitive dysfunction (Fuermaier, et al., 2014). Some of these studies also examined blood flow, endocrine, metabolic, neural, and kinesthetic illusion responses to WBV in the belief that such responses - singularly, in combination or in an additive manner - mediate the effects of WBV on various organ systems. On a behavioral level, WBV treatments often target the ability to generate maximal voluntary force and power. Findings concerning such

properties are often controversial especially in the area of neuromuscular function. For example, some authors reported that WBV was effective (Kennis, et al., 2013) and others explicitly suggested that it is ineffective (Pollock, Woledge, Mills, Martin, & Newham, 2010) for improving muscle size in old adults. After initial claims and suggestions concerning how WBV acts through neural mechanisms and increases the mechanical output of muscle (Bosco, Cardinale, & Tsarpela, 1999; Bosco, Colli, et al., 1999; Bosco, et al., 2000; Cardinale & Bosco, 2003), there is virtually no evidence for such mechanisms to operate (Cochrane, 2011; Hortobágyi, Rider, & Devita, 2014; Nordlund & Thorstensson, 2007; Ritzmann, Kramer, Gollhofer, & Taube, 2013). Indeed, numerous studies have now demonstrated a wide range of reflex responses to WBV. Most authors reported a deep and in a few cases even a long-lasting depression of the electrically and mechanically evoked reflexes at rest without any facilitation of reflexes during strong muscle contraction (W. J. Armstrong, et al., 2008; Games & Sefton, 2013; Hopkins, et al., 2009; Hortobágyi, et al., 2014). Only few studies conducted with healthy volunteers reported the originally expected reflex facilitation (W. J. Armstrong, et al., 2008; Pollock, Woledge, Martin, & Newham, 2012).

A particularly contentious topic is whether WBV can induce acute and chronic adaptive processes in competitive and/or elite athletes resulting in performance enhancements. This is a relevant issue because the margin of difference between finalists in any sport discipline is becoming ever narrower. Therefore, a re-analysis of the relevant literature appears timely because this topic was reviewed for the last time over a decade ago (Cardinale & Erskine, 2008; Issurin, 2005) or was reviewed for only one specific outcome, i.e., counter movement vertical jump, which is not a general marker of athletic performance and may not be relevant to 'athletic performance' (see Discussion) (Manimmanakorn, Hamlin, Ross, & Manimmanakorn, 2014). In addition, these and other previous reviews included subjects with highly varying levels of physical fitness, ranging from unskilled sedentary old adults to highly trained young ballerinas (Manimmanakorn, et al., 2014).

In the present paper we take a conservative approach that counters the prevailing view in the literature and consider the hypothesis that WBV has probably little or no acute and chronic effects on athletic performance in competitive and/or elite athletes. We argue that the proportion of stimulus that comes from WBV as part of the total conditioning stimulus provided by exercise training and other prophylactics (i.e., massage, nutrition, ergogenic aids) is so small that it cannot substantially improve athletic performance or act as an additional ergogenic aid. In addition, the nature of the stimulus provided by WBV is not specific to the structure of the motor skills involved in sport-specific tasks. Even if a rapid and transient conditioning effect in the form of e.g., an

increase in muscle power should occur, there is no enabling mechanism mediating the incorporation of this improved muscle power into the kinematic and kinetic structure of the sport-specific target task. While exposure to WBV in a semi-squat, albeit static, position could improve vertical jump height, athletes rarely if ever execute jumps in the form and conditions used in a laboratory environment. Although WBV is often combined with skills that constitute athletic performance itself (i.e., baseball batting with and without WBV), the environmental and competition constraints would most likely interact with the small changes invoked by the WBV stimulus. The focus of the present scoping review is to examine the above-mentioned hypothesis and determine if WBV can increase athletic performance in competitive and/or elite athletes.

METHOD

We examined the effects of WBV on measures frequently used as proxy for athletic performance such as jumping and also 'athletic performance' representing a specific sport discipline such as Olympic skeleton, softball batting, and sprinting. According to the principles of a scoping review, we intended to: keep the research question broad (i.e., can WBV increase athletic performance); define strict study inclusion later based on the results of the present preliminary appraisal, and provide a qualitative instead of quantitative assessment vis-à-vis, methods adopted by systematic review and meta-analyses (R. Armstrong, Hall, Doyle, & Waters, 2011). We identified relevant studies listed in reviews with the key inclusion criterion that the subjects were elite and/or competitive athletes, i.e., experts in their discipline, who conduct high performance exercise training and have already achieved the highest performance level in their specific sport at a national and / or international level (Lesinski, et al., 2013, 2014). We have thus excluded studies that examined 'competitive' and/or 'elite athletes' but did not use a comparison control group or control conditions (Bosco, Colli, et al., 1999; Bunker, Rhea, Simons, & Marin, 2011), had insufficient data (Mester, Kleinoder, & Yue, 2006), failed to specify the athletic level or the level was too low (i.e., 'recreational athletes', 'physical education students', 'sports club', 'amateur', 'non-competitive') or the athletes were too young to represent elite performance levels (Bosco, et al., 1998; Delecluse, Roelants, Diels, Koninckx, & Verschueren, 2005; Fachina, et al., 2013; Fagnani, Giombini, Di Cesare, Pigozzi, & Di Salvo, 2006; Fort, Romero, Bagur, & Guerra, 2012; Issurin, Liebermann, & Tenenbaum, 1994; Jones, Parker, & Cortes, 2011; Mahieu, et al., 2006; Oosthuysen, Viedge, McVeigh, & Avidon, 2013; Reyes, Dickin, Crusat, & Dolny, 2011; Reyes, Dickin, Dolny, & Crusat, 2010; Rhea & Kenn, 2009; Rønnestad, 2009a, 2009b; Rønnestad & Ellefsen, 2011; Wyon, Guinan, & Hawkey, 2010), or measured features of athletic performance (i.e., gait kinematics) but not performance

itself (Padulo, Filingeri, et al., 2014). Except for one study (Kinser, et al., 2008), we also excluded studies that applied vibration focally directly to the muscle belly or tendon, through probes or hand-held devices and cables (Cochrane & Hawke, 2007; Issurin, et al., 1994) and used frequencies over 50 Hz. In summary, we examine the acute and chronic effects of WBV on a) maximal voluntary force and power as proxies for athletic performance; b) flexibility and joint range of motion, and c) on athletic performance.

Effects of WBV on maximal voluntary force in athletes

Acute effects. We have identified two studies that examined the acute effects of WBV on maximal voluntary torque and strength in elite athletes (Lovell, Midgley, Barrett, Carter, & Small, 2013; Ronnestad, Holden, Samnoy, & Paulsen, 2012). One study compared the effects of WBV (40 Hz, 0.83 mm), field-based agility re-warm-up, and seated rest on maximal voluntary torque in semi-professional soccer players ($n = 10$, age 20). The players received these treatments during half time of a simulated soccer match to determine if WBV compared with the control treatments (i.e., field-based agility re-warm-up, and seated rest) could reduce torque loss more effectively upon return to the field for the second half. Over the 90-min simulated game, peak torque declined ($p < 0.01$). However, between the end of the first half and start of the second half, the most critical period, when WBV was applied, maximal quadriceps concentric torque decreased by 6.4% (WBV: 238.3 vs. 223.1 Nm), remained unchanged after agility re-warm-up (0.4%, active control), and increased by 4.3% after seated rest (passive control). There were no differences between half-time interventions with respect to eccentric hamstring torque across time and between groups. These data suggest no sparing effect of WBV on MVC torque under these conditions. The authors' broader analyses also showed no statistical differences between WBV and the agility (active) control treatment.

The second study also used a within subjects design and compared the performance in 1RM squat performed with and without WBV (50 Hz, 3.0 mm) in national level male power lifters ($n = 12$, age 24). There was no effect of WBV on the weight lifted with (210 kg) and without (211 kg) WBV. Altogether the limited data from these two studies suggest no acute beneficial effects of WBV on maximal voluntary torque and strength in elite athletes.

Chronic effects. We have identified four studies that examined the chronic effects of WBV at a frequency of 33 Hz (range 25 to 40) and amplitude of 4.5 mm (range 4 to 6) administered over an average of 6.0 weeks (range 4 to 8) in 34 male and 47 female competitive and/or elite athletes ($N = 81$), including basketball and volleyball players, track and field athletes, and gymnasts {Colson, 2010 #359; Fagnani, 2006 #361; Preatoni, 2012 #364; Wang, 2014 #365}. These studies measured maximal strength performance in the form of MVC knee

extension force or torque on an isokinetic dynamometer or 3RM leg strength with free weights. The average increase in maximal strength was 14% when athletes performed the training exercises in combination with WBV and it was 5% when they received WBV only. Further, the increase in maximal strength was 4% after active and 1% after passive control interventions.

Results in two of the four studies were statistically significant with respect to WBV treatment (Fagnani, et al., 2006; Wang, et al., 2014). Isometric and eccentric knee extension MVC torques increased by 21% and 23% (both $p < 0.05$) following four weeks of static strength training at 75% of standing 1RM combined with WBV in national level sprinters (Wang, et al., 2014). Training with WBV alone resulted in 10% and -7% (both n.s.) changes in isometric and eccentric knee extension MVC torques. These torques did not change with strength training (1%, active control). When competitive volleyball players, basketball players, track and field athletes, and gymnasts performed their event-specific exercises on a WBV platform, 3RM leg press increased by 12.7% or 48 kg to 426 kg ($p < 0.05$) compared with the 10 kg gain (n.s.) in passive control subjects (Fagnani, et al., 2006). However, the control vs. the intervention group's initial 3RM was 16 kg higher, suggesting a lower adaptive reserve in the control group. In contrast, strength training with WBV failed to increase isometric knee extension MVC significantly (10%) and more than strength training without WBV (also 10%) in national level soccer and softball players (Preatoni, et al., 2012). There also was only 5% and 0% increase in isometric knee extension MVC force after 12 sessions of squat exercise with and without WBV in a group of competitive basketball players (Colson, Pensini, Espinosa, Garrandes, & Legros, 2010).

Taken together, there is inconsistent evidence that chronic exposure to WBV in up to 16 sessions delivered over up to eight weeks would reliably increase maximal leg strength in diverse groups of athletes. The data suggest that coaches could expect some beneficial effects of WBV on maximal leg strength in some athletes if they perform training exercises using forceful muscle contractions (over 75% 1RM) in combination with WBV.

Effects of WBV on maximal power generation in athletes

Acute effects. We have identified eight studies that determined the acute effects of WBV at an average frequency of 35 Hz (range 26 to 50) and amplitude of 3.3 mm (range 0.83 to 6.4) on a direct or a proxy measure of leg power in competitive and/or elite athletes (Cochrane & Stannard, 2005; Crow, Buttifant, Kearny, & Hrysomallis, 2012; Despina, et al., 2014; Kinser, et al., 2008; Lovell, et al., 2013; Naclerio, et al., 2014; Rhea & Kenn, 2009; Ronnestad, et al., 2012). These studies included 84 male and 87 female ($N = 171$) athletes ranging in experience between college and Olympic levels, representing a variety of sports

(field hockey, Australian football, rhythmic and standard gymnastics, soccer, football, baseball, track and field, and power lifting). Leg power was measured during squat or jumping exercises before and after a short-term intervention. Because jumping height correlates highly with leg power, many studies used jump height and flight time as a substitute for leg power.

There were minimal acute effects of WBV on leg power compared with active controls. The increase in leg power was 3% after WBV and the change in leg power after active control was 0.4%. For example, leg power measured in the form of countermovement vertical jump height increased 8% in 18 female elite field hockey players ($p < 0.05$) and decreased 3% (n.s.) in the same athletes after cycling as an active control (Cochrane & Stannard, 2005). Changes after the cycling control treatment is not unexpected because low cadence cycling, i.e., 50 RPM, can have unfavorable effects on jumping performance (Marquez, Mon, Acero, Sanchez, & Fernandez-del-Olmo, 2009). In contrast, leg power during vertical jump was 4,267 W or 6.5% lower ($p < 0.05$) than during the active gluteal strength exercise control condition (4565 W) in the same 22 elite Australian football players. When 10 semi-pro soccer players performed WBV and agility re-warm-up during the half time of a simulated soccer match, the effects of the two treatments were negligible and similar (2% and 1%) (Lovell, et al., 2013). WBV had the largest acute effect on leg power in 15 American college football players. Power, measured during drop jumps before and after several bouts of squats at 80% 1RM, increased by 13% and 4% with and without WBV (Naclerio, et al., 2014). However, these changes were not significant and the power production was numerically almost identical after treatment with (2360 W \pm 461) and without WBV (2324 W \pm 506). Leg power was also similar (n.s.) when 12 national level power lifters performed squat jumps using a 65 kg load with (2016 W \pm 483) and without WBV (1943 \pm 499) or using a 100 kg load with (1975 W \pm 593) and without WBV (1896 W \pm 552) (Rønnestad, et al., 2012). The acute effects of WBV (3%) compared with passive control (-2%) were also small. The largest difference (14%, $p < 0.05$) in favor of WBV vs. passive control in leg power occurred in American football players, performing drop vertical jumps after 80% 1RM squats with WBV vs. rest (Naclerio, et al., 2014). In the other seven studies the net effect of WBV was small and statistically not significant: 7% (Cochrane & Stannard, 2005), -10% (Crow, et al., 2012), 5% (Despina, et al., 2014), 0% (Kinser, et al., 2008), -6% (Lovell, et al., 2013), and 4% (Rhea & Kenn, 2009; Rønnestad, et al., 2012). Together, the data suggest minimal or no immediate effect of WBV on leg power measured directly or indirectly in competitive and/or elite athletes.

Chronic effects. We have identified seven studies that examined the chronic effects of WBV at an average frequency of 34 Hz (range 25 to 40) and amplitude of 5.0 mm (range 4 to 8) over 8.3 weeks (range 4 to 14) in 13 male and 127

female (N = 140) dancers, basketball, soccer, softball, and volleyball players, track and field athletes, gymnasts (Annino, et al., 2007; Colson, et al., 2010; Fagnani, et al., 2006; Fernandez-Rio, Terrados, Fernandez-Garcia, & Suman, 2010; Fernandez-Rio, Terrados, & Suman, 2012; Marshall & Wyon, 2012; Perraton, et al., 2011). Exercise training included, with or without WBV, loaded and unloaded squat exercises, practice of discipline skills, and strength training. Leg power was measured before and after interventions during a single vertical jump (in ms, cm), a series of vertical jumps, squat, and leg press.

The average increase in leg power was 9% as a result of WBV training alone or in a combination with exercise, and the increase was 7% and 5% after active and passive control interventions. After 24 sessions of squat exercises the control-group adjusted increase in vertical jump height, a proxy measure of leg power, was 8% in elite dancers ($p < 0.05$, t-test and Bonferroni adjusted)(Annino, et al., 2007). However, in this study the initial difference in jump height between the two groups was greater than the change produced by the intervention. In fact, the post-intervention values were numerically identical, 28.5 cm (Annino, et al., 2007). The two groups also substantially differed in power by 81 W measured during leg press against 100 kg load at baseline and the active control vs. the WBV group generated actually 65 W more power at post-test. The second study reported a net of 7% greater gain in leg power after intervention during which a mix group of elite athletes who practiced discipline skills with or without (control) WBV (Fagnani, et al., 2006). Again, the post-intervention values were only 0.6 cm different (31.9 vs. 31.3 cm).

In total, the results from these seven studies conducted in competitive and/or elite athletes suggest little and inconsistent evidence for WBV alone or in combination with exercise, to increase leg power.

Effects of WBV on flexibility in athletes

Acute effects. We have identified three studies that examined the acute effects of WBV at 29 Hz frequency (range 26 to 30) and 3.3 mm amplitude (range 2 to 6) on flexibility in competitive and/or elite athletes (Cochrane & Stannard, 2005; Despina, et al., 2014; Kinser, et al., 2008). These studies included 81 female field hockey players, gymnasts, and rhythmic gymnasts. Flexibility was measured using the sit-and-reach test and front splits before and after short-term WBV alone, WBV combined with squats, or focal vibration of body parts during stretching. Active control conditions included cycling and stretching without vibration exposure.

Overall, the increase in range of motion was 9% after WBV or WBV combined with exercise, 5% and 2% after active and passive control. Two of the three studies reported significant effects of vibration on flexibility (Cochrane &

Stannard, 2005; Kinser, et al., 2008). Standing on the vibration platform for a few bouts increased range of motion by 8% in elite field hockey players ($p < 0.05$) while the change was 6% and 5% after active (cycling) and passive control (n.s.) (Cochrane & Stannard, 2005). Although the group by time interaction was significant, note that the difference between WBV and active control (cycling) in sit-and-reach performance was only 1.3 cm after the two interventions. Elite young gymnasts were also able to lower themselves 18% deeper ($p < 0.05$) in the front split after vibration of specific body areas while assuming various stretching positions (Kinser, et al., 2008). However, we note that not only vibration but also the initial level of the front split might have affected the changes because the vibration+ stretch group's front split was 6 cm poorer (26.2 cm relative to the floor) compared with the vibration only (20.2 cm) and 7 cm poorer (19.4 cm) compared with the stretch only control. There was virtually no effect (1%) of WBV performed in the squat positions by Olympic level rhythmic gymnasts (Despina, et al., 2014). Taken together, WBV and vibration of focal body parts can probably improve flexibility to a small extent but inconsistently.

Chronic effects. We have identified two studies that examined the chronic effects of WBV at an average frequency of 30 Hz (range 25 to 35) and amplitude of 6.0 mm (range 4 to 8) over 6 weeks (range 4 to 8) in 41 female competitive and/or elite athletes (Fagnani, et al., 2006; Marshall & Wyon, 2012). Dancers, volleyball and basketball players, track and field athletes, and gymnasts practiced their discipline-specific movements with WBV and in the active control condition without WBV. Exercise training included, with or without WBV, a practice of discipline movements (half squats, loaded and unloaded squat exercises) and strength training. Flexibility was measured using the sit-and-reach test (Fagnani, et al., 2006) or by measuring the active hip range of motion in a specific dance position (Marshall & Wyon, 2012).

Both studies revealed statistically significant effects of WBV on flexibility. The increase in sit-and-reach was 3.0 cm or 15.3% ($p < 0.0$) compared with the active control (1.2 cm, 7%) so that the post-intervention values also revealed a 3.0-cm between-group difference (Fagnani, et al., 2006). WBV also improved hip range of motion in dancers (99.9° vs. 117.5°, 17.6%, $p < 0.05$) with no change in active controls (1.8° or 1.7%, n.s.). However, these effects may not be solely due to WBV because there was a difference of 5.4° between the pre-intervention values (WBV: 99.9°, active control: 105.3°). In total, the data suggest a clear and consistent chronic effect of WBV on joint flexibility in the form of range of motion.

Effects of WBV on athletic performance in athletes

Acute effects. We have identified seven studies that determined the acute effects of WBV at an average frequency 36 Hz (range 25 to 50) and amplitude of 3.8 mm (range 0.83 to 13.0) on athletic performance in competitive and/or elite athletes (Bullock, et al., 2008; Dabbs, et al., 2010; Despina, et al., 2014; Guggenheimer, Dickin, Reyes, & Dolny, 2009; Lovell, et al., 2013; Padulo, Di Giminiani, et al., 2014; Ronnestad, Slettalokken, & Ellefsen, 2013). These studies included 66 male and 39 female (N = 105) athletes ranging in experience between college and Olympic levels representing a variety of disciplines (ice hockey, rhythmic gymnastics, skeleton, soccer, softball, track and field). The acute interventions included squats, batting, high knee running, and shuttle runs so that WBV was added to or combined with these activities. Active control conditions included the same (i.e., squats, dry batting, etc.) or other (i.e., agility) exercises and passive control involved rest. We expressed the data so that improvements in performance (i.e., decrease in sprint time, increase in velocity) were set to positive percent changes and decrements in performance were set to negative percent changes.

Considering the seven studies, the acute effects of WBV alone or added to specific activity were minimal. The average increase in athletic performance or in its proxies across the seven studies was -0.3% (range -12% to 7%). Three of the seven studies reported significant acute effects of WBV on athletic performance (Despina, et al., 2014; Padulo, Di Giminiani, et al., 2014; Ronnestad, et al., 2013). For example, one of three measurements revealed a 7% increase ($p < 0.05$) in rhythmic gymnasts' balancing ability 15 minutes after squat type of exercises performed with WBV compared with the -1.0% change (n.s.) when the athletes performed the same exercises without WBV. However, there were no changes in the same measure one minute after WBV and the changes in another type of balance measure, i.e., weight shift, were -2% (WBV) and -3.3% (active control) (both n.s.). When, in a second study, soccer players completed seven 40-m shuttle sprints, as expected, fatigue impaired 40 m sprint time by 7.3% or 0.52 s ($p < 0.05$). However, the deterioration in sprint time was almost 4% or 0.3 s less when the athletes were exposed to WBV compared with no exposure to WBV (Padulo, Di Giminiani, et al., 2014). Finally, WBV as a pre-conditioning exercise also had a small but statistically significant effect on semi-pro ice hockey players' 10 and 20 m sprint time, which improved by 1.8% or 0.03 s (10 m) and by 1.1% or 0.03 s (both $p < 0.05$) (Ronnestad, et al., 2013). However, WBV had no significant acute effects on sprint time in sprinters (Guggenheimer, et al., 2009), skeleton athletes (Bullock, et al., 2008), and soccer players (Lovell, et al., 2013) and on softball players' bat speed (Dabbs, et al., 2010). Taken together, there is little and inconsistent evidence that WBV would

increase athletic performance or proxies of athletic performance in athletes in the short run.

Chronic effects. We have identified two studies that examined the chronic effects of WBV on athletic performance in 34 male and 7 female (N = 41) competitive and/or elite athletes (Delecluse, et al., 2005; Wang, et al., 2014). When elite sprinters trained for five weeks with and without WBV (35 Hz, 2 mm), the start time for 30 m sprint did not change (364.3 ms both pre and post with WBV; pre: 374.2 ms, post: 375.2 ms without WBV) (Delecluse, et al., 2005). Likewise, the 30 m sprint start velocity, i.e., horizontal velocity of the center of mass leaving the blocks) remained unchanged with (2.74 vs. 2.72 m/s) and without WBV (2.83 vs. 2.83 m/s) (Delecluse, et al., 2005). In contrast, the change in 30 m sprint velocity was 0.16 m/s (to 7.01 from 6.85 m/s, $p < 0.05$) after 4 weeks of static squat exercise training during which athletes pressed up against an unmovable bar at 75% MVC effort while standing on the WBV platform (30 Hz, 4 mm) (Wang, et al., 2014). However, when the same athletes were exposed to WBV only without muscle contraction, the change in 30 m sprint velocity was -0.25 m/s (i.e., there was a decrease in sprint velocity to 6.37 from 6.62 m/s, $p < 0.05$). Exercise training with 75% MVC did not affect running velocity (pre: 6.72 vs. post: 6.75 m/s, n.s.). Taken together, there is limited and inconsistent evidence for WBV to improve athletic performance in athletes.

DISCUSSION

As reported in 19 studies, WBV had an overall 2.5% acute effect on MVC force (-2.1%), power (3.1%), flexibility (9.2%), and athletic performance (-0.2%) in 379 (172 male, 207 female) athletes representing 11 sports. Only 9 or 33% of the 27 comparisons between WBV and active control were statistically significant. There were three comparisons that revealed statistically significant inferior effects of WBV on performance. In 15 studies, WBV had an overall 10.3% chronic effect on MVC force (14.4%), power (9.1%), flexibility (16.5%), and athletic performance (1.1%) in 303 (81 male, 222 female) athletes representing seven sports. Nine or 55% of the 19 comparisons between WBV and active control were statistically significant. Taken all the data from the 34 studies, WBV increased acute and chronic performance by 6.4% in 682 (253 males, 429 female) athletes, representing 14 sports. However, only 18 or 44% of the 46 comparisons between WBV vs. active control were statistically significant. One WBV vs. control comparison revealed a statistically significant inferior WBV-effect. Strictly speaking of 'athletic performance', the acute and chronic WBV-effect, respectively, was -0.3% and 1.1%. We interpret these data to mean that WBV has probably negligible and most likely unreliable acute and chronic effects on athletic performance in competitive and/or elite athletes.

Acute effects. To the best of our knowledge the present paper is the first to review the acute and chronic effects of WBV on athletic performance in competitive and/or elite athletes. Although a previous review some 10 years ago addressed the topic as 'WBV in sport' and included many non-elite athletic groups as subjects ('physical education students', 'recreational athletes', 'former high class kayakers', 'healthy men', and 'untrained subjects') (Issurin, 2005). The studies in that review were also varied because participants received vibration through WBV platforms, cables, and other vibrating devices. A recent review was more focused and did compare the effects of WBV on performance in athletes vs. sedentary subjects in a sub-analysis but the performance was only in one specific outcome, i.e., countermovement vertical jump which may have low ecological validity for 'athletic performance' (Manimmanakorn, et al., 2014).

The premise of the present review was that WBV alone or added to movements and exercises athletes use in their preparation for competition would increase athletic performance to a small extent. We based this argument on the notion that WBV, as done in research studies, represents too small a portion of the total training stimulus in terms of the intensity, duration, and frequency. There is some support for this argument in previous data showing that the WBV-effect on jump performance was only about half of the effect size (0.59) observed in untrained healthy adults (0.96), suggesting a diminishment of the WBV-effect with increasing training status (Manimmanakorn, et al., 2014): the higher level an athlete is, the less likely WBV will have a performance-enhancing effect. That review identified only five studies using WBV for longer than 10 minutes and showed that duration of exposure to WBV affected the outcomes (less than 10 minutes: 0.68; longer than 10 minutes: 0.92)(Manimmanakorn, et al., 2014). Exposure of athletes to vibration for as short as 10-20 per minutes per session in relation to practice of skills for 1-2 h (or 10% of total duration, (Colson, et al., 2010)) and the extra time spent on conditioning dilutes and trivializes the WBV-effect. We also note that including the present review none of the studies addressed the issue as to how long after the end of the exposure to WBV would there be an increase in athletic performance. In the setting of track and field, gymnastics, rhythmic gymnastics, and possibly other sports it is impossible to receive WBV up to perhaps 30 minutes before the actual start of the competition and in some sports as in soccer, regulations limit half-time warm-up (Lovell, et al., 2013). Therefore, a combination of logistical and physiological factors makes it unlikely for WBV to have a putative performance enhancing, acute, effect on highly trained athletes' competition performance. The overall 2.5% increase in force, power, flexibility,

and athletic performance observed in the present review strongly supports these arguments.

Our analysis revealed virtually no acute effects of WBV on MVC force (-2.1%), leg power (3.1%), and athletic performance (-0.3%) and further weakening the WBV-effect is the result that about 70% of the comparisons were statistically not significant, in particular in relation to active controls. It is thus unlikely that athletes would benefit physiologically or through a motor control mechanism (e.g., warm-up effect, novelty effect) from WBV performed immediately before competition. We also note that a majority of the acute interventions were done in the off-season period when training intensity and volume are both low and, if at any time during the season, any extra effect due to WBV would have had the greatest probability to manifest itself but it failed to do so.

Chronic effects. While the percent changes in MVC force (14.4%), power (9.1%), flexibility (16.5%), and athletic performance (1.1%) seem to reflect greater overall (10.3%) chronic than acute (2.5%) responsiveness to WBV relative to active control, only 9 or 55% of 19 comparisons were statistically significant. A substantial weakness of this analysis is that there are only two chronic intervention studies that examined the effects of WBV on what we categorized as 'athletic performance', sprinting (Delecluse, et al., 2005; Wang, et al., 2014). One of these studies revealed numerically identical 30 m start times (364.3 ms both pre and post 5 weeks of sprint training combined with WBV, n.s.) and reported also no changes in 30 m start velocities (pre: 2.74 and post: 2.72 m/s, n.s) (Delecluse, et al., 2005).

However, even the significant comparisons were fraught with methodological problems because, as detailed in the respective sections previously, there were numerous studies which reported significant group by time interaction effects but: 1) the difference between the initial values in the two groups or conditions were greater than the effect produced by the WBV treatment, favoring the changes in the WBV group; 2) in several studies post-values were actually higher in the control group or control conditions compared with the post treatment values in the WBV experimental groups; 3) several studies measured multiple outcomes and based the conclusions on the significant effects, omitting the non-significant comparisons; 4) while the changes were statistically significant, functionally were probably not relevant (i.e., 0.03 s improvement in ice hockey sprint time), and 5) several studies used incorrect statistical analyses. Such issues question the reliability of the findings and the interpretation of the data.

Of all groups, outcome measures, and interventions, WBV had the most consistent statistically significant and functionally meaningful chronic (but not acute) effects on flexibility (16.5% vs. 4.1% active control) (Fagnani, et al., 2006;

Marshall & Wyon, 2012). How such an increase in flexibility might occur is unknown. The authors of these articles suggest that vibration causes analgesic effects, allowing athletes overcome pain and achieve a greater range of motion. The authors refer to studies in which vibration was used to determine the effect of conditioning vibratory stimulation on pain threshold of the human tooth (Ekblom & Hansson, 1982) or examined the effects of vibratory stimulation as a pain-relieving agent in patients who suffered from chronic musculoskeletal pain (Lundeberg, 1984). These, and many other clinical studies referenced in reviews, used 10 or 100 Hz focal vibration to relieve pain. WBV studies however never use such frequencies and 10 Hz is deemed actually potentially harmful in the context of WBV (Rittweger, 2010). These authors (Fagnani, et al., 2006; Marshall & Wyon, 2012) also argue in favor of a thermic effect on flexibility through increased blood flow but one study found actually a greater decrease in muscle temperature with WBV compared with agility control during the half time in a simulated soccer match (Lovell, et al., 2013). It is also perplexing that the WBV-generated energy associated with the acceleration rapidly dissipates as it progresses from the ankle to hip soft tissue structures (Friesenbichler, Lienhard, Vienneau, & Nigg, 2014), yet the significant chronic WBV-effect occurred in hip joint flexibility where the WBV-effect is the weakest. Thus, how the 12-13% net chronic (but not acute) effects of WBV on range of motion come about remains unknown.

Concluding comments, recommendations, limitations. Dozens of studies examining the acute and chronic effects of WBV on MVC force, leg power, flexibility, and athletic performance used 'passive control', a comparison the present review tends to de-emphasize. We suggest that the passive control comparisons are not valid because the WBV groups experience extra muscle activation or even perform extra work (as suggested by oxygen uptake measurements), factors that are absent in passive control groups.

Second, virtually all of the studies in competitive and/or elite athletes were completed off-season. One would predict that the low efficacy of WBV observed in the present review might become even lower when coaches increase in-season training volume and intensity and shift attention to event-specific conditioning.

Third, there is an overwhelming focus in the literature on how WBV might serve as an adjuvant to physical conditioning even though it is likely that WBV may have some unquantified effects on motor control. Of the 34 studies reviewed here, there was only one that examined postural adaptations (i.e., weight shift) and balance in professional dancers, not quantity but quality of performance (Despina, et al., 2014). Would WBV compromise or enhance basketball players' ability to execute jump shots and free throws accurately? Would acute WBV positively or negatively affect tennis players' ability to serve

accurately and fast? In general, what is the effect of WBV on force control, steadiness, and accuracy? In this context, it has to be clarified whether WBV also produces kinesthetic illusions as reported for single muscle vibrations at high frequencies (Goodwin, McCloskey, & Matthews, 1972a, 1972b, 1972c; Taylor & McCloskey, 1991).

Fourth, many study, mistakenly, claim the use of sham WBV (Colson, Petit, Hebreard, Tessaro, & Pensini, 2009; Cormie, Deane, Triplett, & McBride, 2006; Delecluse, Roelants, & Verschueren, 2003; Marin, Ferrero, Menendez, Martin, & Herrero, 2013; McBride, et al., 2010; Mikhael, Orr, Amsen, Greene, & Singh, 2010; Petit, et al., 2010; Torvinen, et al., 2002). These and many other studies had subjects perform the experimental tasks on the WBV platform with the vibration turned off. However, such vibration is not truly sham. The key issue with sham WBV is the concealment of the mechanical component, i.e., vertical vibration. It was previously reported that real and sham WBV resulted in similar changes in bone metabolism and two middle-aged post-menopausal volunteers in the sham group also reported adverse effects (Turner, et al., 2011). Rogan et al reported a significant effect in favor of real vs. sham WBV in only one of 10 comparisons (Rogan, Hilfiker, Schmid, & Radlinger, 2012). Truly sham WBV also produced about one half of the changes in reflex excitability ($p < 0.05$) (Hortobágyi, et al., 2014). Sham or placebo can act through physical, biological, and behavioral paths. Athletes naïve to WBV who, when tested or trained, hear the humming of the motor, see the number on the frequency display, and thus believe that they receive true treatment while in fact they stand on a platform in which the motors have been detached from the platform, very likely would exhibit strong placebo effects, similar to those reported previously (Hortobágyi, et al., 2014; Rogan, et al., 2012; Turner, et al., 2011). Such an effect would further minimize the true effects of WBV on motor performance. One of the strongest pieces of evidence suggesting a potential placebo effect associated with WBV is the finding that the active exercise control interventions most often failed to produce a significant effect but when the same interventions in separate studies were administered, the effects were larger and significant. WBV alone and strength training alone did not improve performance but WBV added to strength training did. Further, strength training normally increases strength but strength training in many WBV as active control failed to increase strength.

Finally, most studies invoke, recently mostly debunked, 'neural mechanisms' to explain the WBV-effect on motor performance (Cochrane, 2011; Hortobágyi, et al., 2014; Nordlund & Thorstensson, 2007; Ritzmann, et al., 2013). But what is actually the mechanism that enables conversion of the increases in motor performance measured in a laboratory test task (i.e., vertical jump power) into 'athletic performance' (sprinting speed, balance, complex

skills)? Under most circumstances, there is a large discrepancy between the nature of the task in which the WBV-stimulus is given and the structure of motor skills making up a sport-specific task. There is little or no discussion in these papers how, for example, performing static squats at 75%MVC load would improve running velocity (Wang, et al., 2014).

One recommendation for future studies is to use only active but not passive control groups. Future studies should specify the net time and the percent of total time athletes received WBV. There is a strong need to include truly sham WBV in the experimental design. The conclusions of many studies are uncertain because, despite randomization, the initial level of performance between WBV and control groups are greater than the WBV effect and the post-treatment values are often actually higher in the control than in the WBV group. Such situations require the use of analysis of covariance with the baseline measures as covariates and the computation of the effects sizes between groups and not only within the WBV, a practice done frequently, resulting in inaccurate conclusions. The preponderance of studies was conducted off-season when the composition of practice and workouts differs vastly from preparation in the competition period. Thus most studies extrapolate the results to a period and conditions that differ from the conditions under which the studies are completed.

The present review is limited by its scoping and qualitative nature (Armstrong, et al., 2011) and will have to be strengthened by appropriate effect size computations. A major limitation is that there were only a handful of studies that examined the acute (6) and chronic (2) effects of WBV on 'athletic performance'. Although several authors responded to our queries and provided the needed data to compute percent changes, an equal number of authors failed to respond or were not reachable and forced us to estimate the data from figures. As in any review, it is possible that certain studies were missed or appeared after the manuscript was completed.

In conclusion, the present scoping review found little and inconsistent evidence that acute and chronic WBV would improve athletic performance in competitive and/or elite athletes.

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