Whole Body Vibration as an Exercise Modality to Prevent Sarcopenia and Osteoporosis

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Keywords

Frailty · Muscle wasting · Skeletal muscle · Bone · Training · Rehabilitation · Old people medicine

1 Introduction: Why We Need to Exercise at Old Age

The end of the human lifespan is characterized by an accumulation of diseases and disabilities. Generalized inflammation (=inflammaging [1]), the inability to match energy expenditure with energy uptake (=metabolic inflexibility [2]), loss of muscle mass (=sarcopenia [3]), deterioration of muscle strength (=dynapenia [4]), bone loss (leading to osteoporosis), and the catastrophic event of fractures are hallmarks of aging that facilitate disease and disability accumulation. This multi-faceted and multi-factorial phenotype is nowadays referred to as the frailty syndrome of old age [5].

The frailty phenotype bears many similarities with the effects of disuse. Thus, immobilization by experimental bed rest readily leads to metabolic derailment [6], muscle atrophy [7] and muscle weakness [8], and bone loss [7]. Older people tend to become generally less active, and they frequently stay in bed because of

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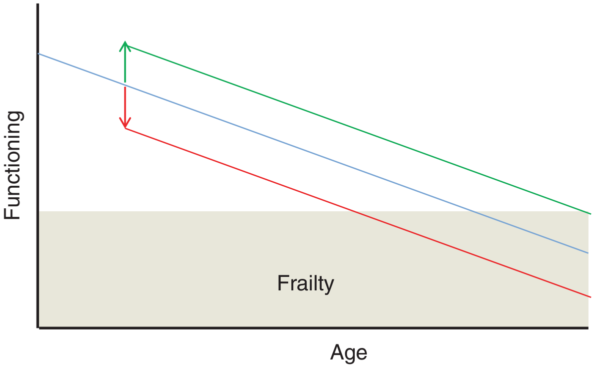

Fig. 1 Conceptualization of the frailty syndrome resulting from the combined effects of (**a**) senescence (blue line), i.e., an irreversible biological program, and (**b**) the beneficial modulatory effects of exercise (green lines) and sedentarism or even disuse (red lines)

health problems, which are strongly associated with deterioration of mobility [9]. Sedentarism and disuse, therefore must be considered as substantial contributors to the frailty phenotype. On the other hand, detrimental immobilization effects recover after reambulation in young people [10, 11]. On the reverse side, virtually all bodily functions decline even in master athletes [12], i.e., in people who maintain extremely high levels of physical activity up to old age. One would therefore think of the frailty phenotype that results from both senescence and age-related sedentarism and disuse (see Fig. 1). From that perspective, the idea to use physical interventions in order to ameliorate frailty severity seems straightforward, but hoping to reverse aging [13] will likely remain futile.

2 Specific Requirements for Physical Training at Old Age

It is widely recognized that physical exercise improves health and well-being at all ages [14]. In the world's populace, however, physical activity levels are declining to alarmingly low levels across all age groups. To combat this pandemic, the World Health Organization [15], the USA Department of Health [16], and national and international scientific and medical societies have all provided guidelines that shall increase levelsof physical activity. However, most older people hesitate to participate in physical exercise programs, in particular of those exercises that are new to them, strenuous, challenging, or time consuming. Also, from a scientific point of view, the classical publications on trainability in older people [17] were performed on highly selected sub-populations, which limits their generalizability. Moreover, many proposed exercise interventions are not easily feasible for geriatric patients because of ailments, co-morbidities, or lack of motivation.

Therefore, old age requires exercise modalities that target the causes of frailty (e.g., musculoskeletal de-conditioning), on the one hand, and are safely feasible within a reasonable time on the other hand. In that sense, the therapeutic usage of whole body vibration (WBV) to halt sarcopenia, dynapenia, and osteoporosis seems a straightforward approach.

3 Whole Body Vibration: The Fundamentals

WBV differs from most other types of exercise in that energy from an external machine is inserted into the human body. This energy transfer is crucial. Physically, vibrations are mechanical oscillations that are characterized by frequency (=number of cycles per unit time), their amplitude (displacement from neutral to peak, or also from minimum to maximum as "peak-to-peak"), and by their shape. As to shape, vibrations are mostly sinusoidal (thus "smooth") in the realm of engineering, but rarely so in biology and physiology (e.g., electrocardiogram). The utilization of vibrations started early on in our evolution. Not speaking of sound and audition, vibration is used as a means of communication in bees in order to inform peers about location and abundance of food, vibration is used by spiders as the source of information on prey in their cobweb, and as a rutting signal by male treehoppers to alert potential spouses.

Most available vibration platforms operate with vertical displacements, and they should produce sine waves to prevent higher frequency components or shocks that could aggravate safety concerns. To elicit a physiological response in our body, vibrating actuators have to be coupled to a bodily interface (typically the foot, see Fig. 2). It is important to realize that energy transfer is complete only when the coupling is fixed. Next, the vibration signals are transmitted through the tissues, and the propagation of the signals depends on the viscoelastic properties of the tissue. If the tissue was purely elastic, then the energy transmission would be complete, and resonance could have catastrophic consequences. However, muscle tissue has viscous, damping properties that dissipate mechanical energy [19, 20], which helps to prevent resonance catastrophe.

Next, we have to consider the human body as being composed of different segments that are connected by joints (see Fig. 2a). Importantly, each joint acts as a viscoelastic spring, and spring stiffness depends on the joint angle. Thus, the transmission of vibration signals for a vibrating footplate increases with erect posture and with stiff muscles. Conversely, vibration transmission can be reduced by assuming a crouched posture, by adjusting muscle tone, and also by placing weight on the fore-foot, as this introduces the ankle joint into the chain. For similar reasons, namely via "adding a joint," side-alternating vibration is associated with smaller vibration transmission to head and trunk than synchronous vibration platforms [21, 22], as side-alternating platforms actuate the lumbo-sacral joint in the frontal plane, which is not the case for synchronous vibration (Fig. 2b).

4 Acute Physiological Responses to WBV

Within the muscle tissue, WBV elicits elongation of the muscle fascicles, tendon stretch and phase-synchronous electrical activation of the acting muscle [23], which is interpreted by most authors as evidence for activation of mono-synaptic stretch

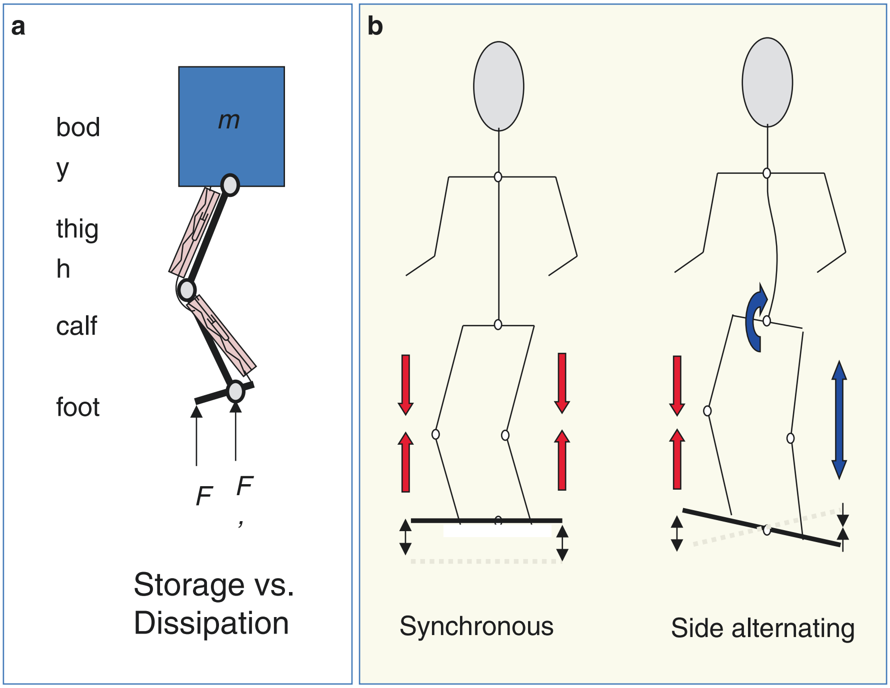

Fig. 2 Physical application of vibration platforms for human exercise. (**a**) The human body can be conceptualized as a mass (= trunk and head) that sits on thigh, shank, and foot, which are linked through joints. Mass and viscoelastic joint properties jointly determine the dynamic response of the human body to vibration. (**b**) Illustration of the two types of vibration platform. Synchronous mode pushes both legs simultaneously, which exempts the lumbo-sacral joint from rotation in the frontal plane. In side-alternating platform, the two legs are pushed anti-phase, and the damping contribution of the lumbo-sacral joint can help to reduce vibration transmission to the head and trunk. Figure reproduced from Rittweger [18]

reflexes [24]. At the same time, vibration does not only elicit stretch reflexes but also inhibits their spinal transmission reflexes [24]. This has been termed "vibration paradox" [25], and it could be explained by mechanisms such as presynaptic inhibition or post-activation depression. In addition, vibration activates cutaneous and Golgi tendon receptors [26, 27], both of which interfere with spinal reflexes.

Muscle stretch is also associated with a rapid increase in muscle temperature [19]. Another immediate response to vibration is the enhancement of blood flow [28], which is depending on the frequency of vibration and, to a lesser extent, on its amplitude [29]. The enhanced perfusion is associated with improvements in muscle tissue oxygenation [30] and is dependent upon the alignment with the gravity vector [31]. Thus, a likely explanation would be that mechanical energy provided by vibration helps to "push" venous blood across venous valves to facilitate the cardiac return.

As one would expect, WBV also stimulates whole body oxygen uptake [32]. This vibration-related excess oxygen uptake scales with the frequency and amplitude of vibration [33], and it seems to be somewhat blunted in older age [34].

5 WBV for Prevention of Sarcopenia and Dynapenia

There is an ongoing debate as to whether greater gains in muscle mass and muscle strength can be achieved in young people by adding vibration on top of traditional exercise, but current studies show either inconclusive or marginal results [35–38]. Although a closer look may reveal specific effectiveness of WBV for calf muscle hypertrophy (as opposed to knee extensor hypertrophy), and that this seems to be related to improvements in reactive power in drop jumps [38], it seems reasonable to conclude that superposition of WBV onto traditional resistive training has only moderate to marginal benefits. Likewise, there has been no significant evidence for the effectiveness of WBV when applying it as a countermeasure against muscle wasting in experimental bed rest, either with or without additional resistive exercise [39, 40].

However, the notion of lacking effectiveness for muscle has to be adjusted when shifting the focus to older people. Thus, several studies that tested the addition of WBV onto standard geriatric conditioning exercise in nursing homes [41, 42] repeatedly report genuine WBV benefits in timed up-and-go and balance (see Table 1). In somewhat younger community dwellers, Bogaerts et al. [47] found beneficial effects of WBV on balance, and Roelants et al. [48] superiority for muscle power for WBV in comparison to standard resistive training. By contrast, a smaller study with lower statistical power did not find a genuine effect of WBV [49, 50]. Osteoarthritis (OA) is a common co-morbidity in old age. In that respect, it is very interesting to note that a genuine benefit by WBV on muscle strength has been demonstrated in elderly women with OA [51]. Overall, as stated by a recent meta-analysis, WBV demonstrates effectiveness to improve muscle strength and power, vertical jump performance and other functional measures [46].

A more detailed picture of the existing literature is given in Table 2. It emerges from this table that WBV is feasible and that it helps on its own to improve muscle power, gait speed, balance, and well-being. The effectiveness is most pronounced in old age and in people residing in nursing homes or in geriatric rehabilitation units (see Table 1). Moreover, combined conventional exercise plus WBV has the potential to achieve more than either of them individually.

6 WBV for Prevention of Osteoporosis

Whereas the majority of interventional WBV studies, if not all of them, that investigated muscular endpoints have used vibration specifications that encompassed peak accelerations greater than 1 g, there have been two competing approaches in the bone field. Both “schools”’ argue that bone tissue strain [64, 65] and strain rate [66] constitute mechanical signals that determine bone modeling and remodeling. However, whereas the first school ascribes the osteogenic strain effects predominantly to peak strains [67], the second school proposed that the effectiveness is a product of the number of strain cycles repetitions as well as their magnitude and that large-magnitude cycles can be replaced by a larger number of low-magnitude strain

Table 1 Randomized controlled trials that tested the effectiveness of WBV for neuromuscular outcomes in geriatric populations. When several publications arose from the same study, they have been collated into the same row of the table

References	Population	Period [months]	N Subjects	Outcome
Ma et al. [43]	Postmenopausal women	≥6	1014	**Lumbar spine aBMD:** Improved in low-magnitude WBV only **Femoral neck aBMD**: No effect
Oliveira et al. [44]	Postmenopausal women	≥6	1833	**Lumbar spine aBMD**: Improved by WBV (flexed and straight knee) **Femoral aBMD**: Improved by WBV with flexed knees **Trochanter aBMD**: Improved by WBV with flexed knees on side-alternating platforms
Jepsen, Thomsen, Hansen, Jorgensen, Masud and Ryg [45]	Age ≥ 50 years	≥6	1839	**Lumbar spine and total hip aBMD, tibia and radius vBMD:** No effect **Fracture rate**: Improved by WBV (risk ratio 0.48) **Falls rate**: Improved by WBV (risk ratio 0.76)
Lau, Liao, Yu, Teo, Chung and Pang [46]	Age ≥ 50 years	1.5–18	896	**Lumbar spine and total hip aBMD:** No effect

CRT chair-rising test; *Ctrl* passive control; Ex: exercise without weights; *fkStand* flexed knee stand; *fkWBV* flexed knee vibration; *FT* fitness training; *lkWBV* locked knee vibration; *N* number of participants in each group; *n.r.* not reported; *PT* standard physical therapy; *Res* resistive exercise with weights; *SE* static exercise; *Squat* squatting exercise; *TUG* timed up-and-go; *saWBV* side-alternating WBV; *Side-alt*. Side-alternating; *Synchr* synchronous; *syWBV* synchronous WBV; vs.; *WBV* whole body vibration

cycles [68]. Accordingly, the high-magnitude philosophy tried to maximize tissue strains and therefore used high-magnitude vibration (characterized by peak vibrations >1 g). The low-magnitude school has applied vibration specifications that were substantially below 1 g peak acceleration. Initial pre-clinical studies were positive for both low- and high-magnitude vibration protocols [69, 70], and initial clinical studies suggested the effectiveness of low-magnitude vibration in children with disabling conditions [71] and osteopenic women [72]. Moreover, the combination of high-magnitude vibration with resistive exercise prevented muscle wasting and bone loss in experimental bed rest in young men [73], and a subsequent study has demonstrated a genuine role for the vibration component [74].

However, further studies have yielded mixed results, and meta-analyses report limited effectiveness of WBV for bone mineral density (see Table 2). Effectiveness seems somewhat stronger for the lumbar spine and for the hip when using

Table 2 Meta-analyses of randomized controlled trials on the effectiveness of WBV for bone outcomes in geriatric populations. For technical reasons, no summary information on age could be extracted

Design	References	Setting	Period [months]	N	Age	Platform	Outcome
WBVvs. Ctrl	Runge et al. [52]	Geriatric rehab clinic	2	20/19	Range 61–85	Side-alt.	**CRT**: Improved in WBV group only
WBV vs. Ctrl	Russo et al. [53]	Outpatient clinic	6	14/15	Mean 61/61	Side-alt.	**Vertical jump power**: Improved in WBV group only
WBV vs. Ctrl	Zhang et al. [54]	Geriatric rehab clinic	2	19/18	Mean 85/85	Side-alt.	**TUG, muscle strength, balance and Well-being**: Improved in WBV group only
WBV vs. Ctrl	Perchthaler et al. [55]	Community dwellers	1.5	13/8	Mean 55/55	Side-alt.	**Jump height**: Improved in WBV group only; **muscle strength and power**: No change
WBV vs. Ctrl	Santin-Medeiros et al. [56]	Community dwellers	8	19/18	Mean 82	Synchr	**Fall risk and Well-being**: No change
WBV + Exvs. Ctrl	Machado et al. [57]	Community dwellers	2.5	13/13	79/79	*n.r.*	**Muscle size and strength, mobility**: Improved in WBV + ex group only; **muscle power**: Deteriorated in ctrl group only
WBV + Ex vs. Ex	Bautmans, Van Hees, Lemper and Mets [41]	Nursing home	1.5	13/11	Mean 78	Synchr	**Balance, CRT and TUG**: Improved in WBV group only
WBV + PT vs. PT	Bruyere, Wuidart, Di Palma, Gourlay, Ethgen, Richy and Reginster [42]	Nursing home	1.5	22/20	Mean 85/79	Synchr	**Balance and Well-being**: Improved in WBV + PT group only; TUG: Improved in WBV + PT > PT groups

(continued)

Table 2 (continued)

Design	References	Setting	Period [months]	N	Age	Platform	Outcome
WBV + Ex vs. Ex	Simao, Mendonca, Avelar, da Fonseca, Santos, de Oliveira, Tossige-Gomes, Ribeiro, Neves, Balthazar, Leite, Figueiredo, Bernardo-Filho and Lacerda [51]	Community dwellers with osteoarthritis	4	7/8	Mean 75/71	Synchr	**Muscle strength**: Improved in WBV + ex group only
WBV + Ex vs. FT vs. Ctrl	Bogaerts et al. [58], Bogaerts, Verschueren, Delecluse, Claessens and Boonen [47]	Community dwellers	12	94/60/66	Mean 67/67/68	Synchr	**Balance**: Improved in WBV + ex > FT > ctrl groups; **muscle strength and power**: Improved in(WBV + ex & fitness) > ctrl groups
WBV +Ex vs. Ex vs. Ctrl	Rees, Murphy and Watsford [49], Rees, Murphy and Watsford [50]	Community dwellers	2	15/13/15	Range 66–85	Side-alt.	**CRT, gait speed, muscle strength and power**: Improved in (WBV & ex) > ctrl groups
WBV +Exvs. Resvs. Ctrl	Roelants et al. [59]	Community dwellers	6	30/30/29	Range 58–74	Synchr	**Muscle strength**: Improved in WBV + ex > res > ctrl groups;**muscle power**: Improved in WBV + ex > res > ctrl groups
syWBV+Exvs. saWBV+Exvs. Ex	Corrie et al. [60]	Outpatient clinic	3	21/20/20	Mean 82/80/79	Side-alt. Vs synchr	**CRT and TUG**: Improved in ex group only; **muscle power**: Improved in syWBV > ex groups

WBV + SE vs. WBV vs. SE vs. Ctrl	Smith et al. [61]	Community dwellers	3	15/15/15/15	Mean 82.2	Synchr	**Balance**: Improved in WBV and WBV + SE groups only; **muscle strength**: In WBV + SE & SE groups only; **functional independence**: Improved in WBV + SE, WBV and SE groups only
WBV vs. WBV + SE	Osugi et al. [62]	Outpatient clinic	6	14/14	Mean 72	Side-alt.	**Balance and TUG**: Similarly improved in WBV and WBV + SE groups; **CRT**: Improved in WBV + SE group only
fkWBV vs. lkWBV vs. fkStand	Mikhael et al. [63]	Community dwellers	3	6/5/8	64/69/62	*n.r.*	**Muscle strength:** Improved in lkWBV group only

aBMD areal bone mineral density, assessed by dual X-ray absorptiometry; *N* total number of subjects (comprising all groups); *vBMD* volumetric bone mineral density, assessed by peripheral quantitative computed tomography side-alternating platforms with flexed knees. However, the effects on bone density are moderate at best. The risk of fracture, however, was reported to be halved by WBV. That a relatively small effect on bone is associated with substantial reductions in fracture rate has also been reported for pharmacological treatment of osteoporosis [75]. However, WBV seems also to reduce the risk of falls [45], and the vast majority of osteoporotic fractures are caused by falls [76]. It, therefore, seems that part of the reduction of the risk to fall is attributable to neuromuscular benefits by WBV. On the other hand, the reduction in falls can only partly explain the reduction in fractures by WBV interventions. A similar observation had been made in a large, prospective exercise study, in which the fracture-to-fall ratio was halved by a multimodal exercise intervention [77]. Although there was no alteration in bone mineral density, one could, of course, try to explain the discrepancy by effects on bone "quality" [78]. However, as an alternative hypothesis, I propose that exercise interventions in old age improve the capability of the neuromuscular system to dissipate kinetic energy and to thereby prevent fractures.

7 Conclusion

In the past two decades of application in geriatric and rehabilitation medicine, WBV has demonstrated good feasibility and a low-risk profile. Evidence is emerging to suggest that important aspects of the age-related frailty syndrome can be mitigated by whole body vibration interventions. This applies to dynapenia and to a lesser extent to sarcopenia, and also to the risks for fall and to fracture, all of which can be improved by WBV. As a caveat, randomized controlled trials are still lacking in extremely frail populations, e.g., in early rehabilitation after intensive care or after stroke. Also, there is a remarkable dearth of studies on metabolic WBV effects in old age. However, given that the relative effectiveness of WBV seems to increase in old age and that acceptance of other types of physical exercise or therapy dwindles, WBV seems particularly suitable in geriatric and rehabilitation medicine.

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