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Original Article

Whole body vibration in cystic fibrosis – a pilot study

J. Roth[1,2], M. Wust[2], R. Rawer[3], D. Schnabel[2], G. Armbrecht[2,4], G. Beller[2,4], I. Rembitzki[5], U. Wahn[2], D. Felsenberg[2,4], D. Staab[2]

[1]Children's Hospital of Eastern Ontario, Ottawa, Canada; [2]Charite University Medicine, Berlin, Germany;
[3]Novotec Medical, Pforzheim, Germany; [4]Center for Muscle and Bone Research, Berlin, Germany;
[5]Physiotherapy Practice, Braunschweig, Germany

Abstract

Introduction: In cystic fibrosis (CF), bone mass deficits as well as a lack of muscle mass and force have been described. The bone mass deficits are thought to be at least in part secondary to the reduced muscle mass. Whole body vibration has recently been suggested as an effective technique to increase muscle force and power. The aim of this pilot study was to evaluate the compliance and safety of a side-alternating, whole body vibration platform in patients with CF and to assess its effects on muscle force, muscle power, bone mass and lung function. **Patients and methods:** Eleven adult CF patients participated in a six-months home-based training programme on a whole body vibration platform. Muscle force and power were assessed with three standard manoeuvres on a ground reaction force plate at regular intervals. Bone densitometry was performed at the spine, the radius and the tibia using quantitative computerized tomography. **Results:** Regular cardiovascular monitoring did not show any critical drop in oxygen saturation or blood pressure. Lung function remained relatively constant with a median FEV1 change [% of norm] of -3.1% (range -7–20). Trabecular density at the spine and parameters of bone density and geometry at the radius and tibia did not show consistent changes. A median decrease of -0.3% (-31.0–17.9) for muscle force and a median increase of 4.7% (-16.4–74.5) for muscle power and 6.6% (-0.9–48.3) for velocity was noted in the two-leg jump. In the one-leg jump, a median increase of 6.7% (-8.5–24.3) for muscle force was measured. **Conclusions:** Whole body vibration was well tolerated in the majority of the study participants. Most patients were able to increase peak force in the one-leg jump. In the two-leg jump, velocity and muscle power increased with equal or decreased muscle force. This may indicate an improvement in neuromuscular and intramuscular co-ordination (and therefore efficiency) with less muscle force necessary to generate the same power.

Keywords: Cystic Fibrosis, Whole Body Vibration, Bone, Muscle, Osteoporosis

Introduction

In patients suffering from cystic fibrosis (CF), a significant increase in life expectancy has been observed over the last decade[1]. With this increase in life expectancy, co-morbidities affecting organ systems other than the lungs or the gastrointestinal tract have become more significant. In this context, deficits in muscle force, muscle power and bone mass are important[1-3]. A low bone mass may lead to rib and vertebral fractures[1], subsequent kyphoscoliosis and a further reduction in lung function. Recent studies have shown that bone deficits in CF can be explained to a large extent by a lack of muscle mass and force[4,5]. Peak muscle forces acting on bone have been described as the single most important factor for bone acquisition and maintenance[6]. In addition to the absolute deficit in muscle mass, a hyperinflated thorax with a reduced compliance and an increased stiffness of paravertebral and intercostal muscles can be observed in CF[1,5]. The increased muscle stiffness precludes optimal neuro- and intramuscular co-ordination, which is a pre-requisite to generate peak forces and power. The aim of this study was to improve compliance of the thorax, increase muscle force and power and reverse the secondary bone mass deficits. For this purpose, a novel whole body vibration training using the Galileo™ platform (Novotec Medical, Pforzheim, Germany) was applied. Depending on the study subjects and the training modalities, whole body vibration can preserve or increase muscle mass and has been

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Corresponding author: Johannes Roth, M.D., Children's Hospital of Eastern Ontario, 401 Smyth Road, Ottawa, Ontario, K1H 8L1, Canada
E-mail: jroth@cheo.on.ca

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shown to be effective in improving neuro- and intramuscular co-ordination, resulting in an increase in muscle power but also muscle force[8-12]. An increase in bone mass has also been observed[12]. Previous studies had shown that the training was tolerated even in patients with a high level of co-morbidity, e.g., after heart transplantation[13].

Patients and methods

Patient characteristics

Eleven adult patients with a confirmed diagnosis of CF were included in the study. No specific requirements with regard to lung function or exercise capacity were set. Exclusion criteria were pregnancy, epilepsy, acute arthritis/tendinopathy at the start of the study, hernias, acute thrombosis and esophageal varices. All patients were seen at regular intervals in the Department of Pediatric Pneumology of the Charite University Medicine, Berlin. Written informed consent was obtained from the patients according to the Declaration of Helsinki. The study protocol had been approved by the Ethics Committee of the Charite University Medicine, Berlin, as well as the German Federal Agency for Radiation Protection.

Study design

The intervention program consisted of a six-months, home-based training with the Galileo home™ platform (Novotec Medical, Pforzheim, Germany). Regular study visits were scheduled at baseline, after two and four weeks, and every month thereafter. A peripheral quantitative computed tomography (pQCT) of the forearm and lower leg and a quantitative computed tomography (QCT) of the lumbar spine were taken at baseline and after six months of training to document the change in various parameters of bone density and geometry. In addition, vertebral fracture assessment (VFA) using X-ray absorptiometry (DXA) was done to document any existing or new vertebral fractures. Where the results for VFA were equivocal, an additional radiograph of the spine was taken to document fractures. Lung function was assessed using a bodyplethysmograph (Jaeger GmbH, Hoechberg, Germany) initially and after three and six months. At each visit muscle force, power, velocity and jump height were measured using a Leonardo™ (Novotec Medical, Pforzheim, Germany) ground force reaction plate. Body height and weight as well as a joint examination and compliance of the thorax were also evaluated at each visit. To assess the flexibility of the spine as an indirect measure of muscle stiffness, the finger-floor-test was applied.

A standardized protocol was used to document changes in disease parameters, medication or side effects of the training. At each visit, the training was performed by the participants to ensure a proper training technique as well as to increase training intensity according to individual progress. Cardiovascular monitoring including blood pressure and oxygen saturation was carried out before, during and after the training at each of these visits.

Galileo device

The Galileo home™ consists of a plate on which the patient stands with a fulcrum along the mid-section of the plate. It delivers a vertical, side-alternating and sinusoidal displacement of the plate on the left and right side of the fulcrum. The frequency of this movement is adjustable. The amplitude increases with the distance from the fulcrum and can thus be varied depending on the positioning of the patient's feet[12]. The maximum amplitude of the Galileo home™ is ±3.9 mm (7.8 mm peak to peak). The person standing on the plate experiences muscle contractions at a high frequency[8,14]. Depending on the posture the patient takes, most muscle groups in the body can be reached. With regard to the physiologic mechanisms it has been shown previously, that the direct application of vibration to muscles or tendons elicits the so called "tonic vibration reflex", an activation of muscle spindles, mediation of the signal via Ia afferent neurons to the spinal cord and subsequent activation of muscle fibres via alpha-motoneurons independent of cortically originating efferent pathways[7,15,16]. Whole body vibration is thought to work via monosynaptic and polysynaptic spinal reflexes as well. Electromyography (EMG) measurements during whole body vibration with the Galileo show a strong increase in reflex muscle activity[9,12,17]. A linear increase in oxygen consumption with a stepwise increase in frequency has been shown[14], suggesting that every vibration cycle elicits a certain amount of metabolic power relative to the muscle contraction[14]. Finally, the neural conduction time necessary for a cortical response to vibration would not be compatible with the frequencies and subsequent muscular responses in WBV[18]. Following training, an increase in stretch reflex amplitude and an increase in muscle spindle sensitivity has also been reported, suggesting that this type of vibration leads to increased neuromuscular recruitment of motor units[8]. In addition to improvement in neuromuscular function, a preservation and increase in muscle mass has been observed[12]. The muscle contractions in response to WBV can be induced along a wide range of frequencies. Frequencies up to 20 Hz decrease muscle stiffness and improve flexibility[19,20]. With frequencies above 20 Hz the physiologic contraction and relaxation time is longer than the time between two impulses from the plate; therefore, the muscle cannot completely relax between two cycles[18]. The result is a tonic contraction and a more exhaustive, anaerobic training. Exhaustive training at high frequencies will lead to the preservation of muscle mass or reactive muscle hypertrophy[21].

Training program

The training consisted of a standardized exercise program. On five days per week, one unit of six minutes duration at a frequency of 12 Hz was carried out to improve the range of motion of the thorax, spine and extremities. On three days per week, one unit of six minutes duration at frequencies up to 26 Hz (according to the individual patient's capabilities) was performed including additional weights of up to nine kilograms to increase muscle power and force. During each unit (12 Hz and 26 Hz), the patient performed standardized manoeuvers including leg bends, trunk bends and extension and rotation of the trunk while standing on the device. At the beginning of the study, participants performed the exercises under supervision and then continued training at home. At each study visit, the training was performed by the participants to ensure a proper training technique as well as to increase training intensity according to individual progress.

Leonardo mechanography

Muscle force, power and velocity were assessed with the so-called jumping mechanography using three standard manoeuvers on the Leonardo™ ground reaction force plate (Novotec GmbH, Pforzheim, Germany) at regular intervals. This device measures forces applied to the plate over time. Therefore, stationary forces as well as the variation in forces over time (ground reaction forces) can be investigated. Using these forces together with the patient's body weight, power, velocity and jump height can also be calculated[22]. The individuals did three manoeuvers on the platform:

1) A two-leg jump was performed as a countermovement jump with freely moving arms and the subjects were instructed to jump as high as possible. This test documents muscle power, jump height and velocity although muscle force and power measured in this test do not represent the maximum values an individual might generate[22]. This method was nevertheless chosen, as changes can be reasonably assessed in longitudinal studies due to the high reproducibility of this test[22].
2) A trunk bend was performed to document muscle force and power of the trunk.
3) A one-leg jump was performed to measure maximum forces.

Peripheral quantitative computed tomography

pQCT measurements were performed at the non-dominant arm and leg using an XCT-2000 scanner (Stratec, Pforzheim, Germany) equipped with a 58 keV X-ray tube. The effective whole body radiation dose is less than 0.9 μSv for each measurement of this study. A scout-view was performed to define the tibio talar and radio carpal joints. Four percent and 66% (60% at the radius) proximal of these articular faces (calculated from the total leg and forearm length), two CT measurements were performed. Each tomographic slice had a thickness of 2.3 mm and was sampled at a voxel size of 0.5 mm^3. The speed of the translational scan movement was set at 15 mm/sec. Image processing and the calculation of numerical values were performed using the manufacturer's software version 5.40. The threshold for cortical bone analysis was set at 710 mg/cm^3. For trabecular bone analysis, the threshold was set at 180 mg/cm^3 and voxels with an absorptiometric density between 45 and 280 mg/cm^3 were interpreted as muscle (CSA muscle with threshold 45 and filter F03F05, c3p1 minus CSA bone threshold 280 and filter F03, c1p1). The following parameters were analyzed: At the 4% site trabecular density expressed as mg/cm^3 was measured. At the 65 % site cortical density in mg/cm^3 and the geometrical parameters bone cross-sectional area (CSA, threshold 280) (cortical CSA including the marrow area), cortical area (bone CSA minus marrow area), marrow area (bone CSA minus cortical area), cortical thickness in millimeters and muscle CSA (CSA muscle minus CSA bone and marrow).

Quantitative computed tomography (QCT)

QCT of the lumbar spine was performed on a Siemens Volume Zoom scanner (Erlangen, Germany) using the Siemens calibration phantom, which contains a water equivalent and a 200 mg calcium hydroxyapatite equivalent. A lateral topogram was performed for slice selection. A single 10 mm slice was obtained at the mid-vertebral level of each of the L1, L2 and L3 vertebral bodies parallel to the end plates. Single energy beam of 80 kVp and 125 mAs was employed. Regions of interest (ROI) for the measurement of BMD were automatically defined in cortical and trabecular bone using the Siemens Osteo-CT system software. The calculated calcium content was expressed in mg hydroxyapatite/cm^3.

Vertebral fracture assessment (VFA)

VFA is a radiographic method using dual X-ray absorptiometry (DXA) to assess vertebral deformities. VFA of the spine was performed on a Lunar Prodigy Advance (GE Healthcare, Madison, WI) in the left lateral position according to the manufacturer's standard guidelines. Images were analysed by an experienced radiologist for vertebral deformations.

Statistical analysis

As only a small number of patients participated in this pilot study, data were analyzed in a descriptive manner.

Results

Characteristics of the study patients

The characteristics of the patients who finished the study are listed in Table 1. Two patients were post-lung transplantation (patient 6 five months post and patient 4 seventeen months post) and one patient was post-liver transplantation (patient 8). The number of courses of intravenous and oral antibiotic therapies that had to be given due to intercurrent infections and in addition to routine antibiotic regimens are also shown in Table 1. As might have been expected from the

Patient no.	Age (y)	Inf. (no.)	Event	Height[m]	Weight [kg]		BMI [kg/m^2]	
		Abx i.v./p.o.			Start	End	Start	End
1	29	1/1		1.65	54.5	54.4	20.02	19.98
2	30	1/3		1.97	79.1	81.6	20.38	21.03
3	21	2/1	D.m.	1.65	50.9	47.5	18.70	17.45
4	41	0/0	Arthr.	1.73	51.9	55.5	17.34	18.54
5	30	0/1		1.68	74.7	76.2	26.47	27.00
6	38	0/1		1.80	79.6	86.4	24.57	26.67
7	37	3/1	HU	1.66	49.5	47.2	17.96	17.13
8	38	0/2		1.56	49.5	48.6	20.34	19.97
Median	33.5			1.67	53.2	54.95	20.18	19.98

General data of the patients who finished the study are shown. Abx= courses of antibiotics (intravenous/oral) which had to be applied in addition to routine antibiotic therapies. D.m.= manifestation of insulin dependent diabetes during study period. Arthr.= development of arthritis. HU= high urgency listing for lung transplantation.

Table 1. General data.

		FEV1 [% norm]		change [%]
Patient no.	0 months	3 months	6 months	
1	56.2	50.3	52.6	-6.41
2	64.4	74.6	74.9	16.30
3	28.1	29.8	30.5	8.54
4	61.7	69.7	74.3	20.42
5	108.0	101.1	101.0	-6.48
6	66.2	56.8	64.2	-3.02
7	27.3	23.3	25.4	-6.96
8	62.5	63.4	60.5	-3.2
Median	62.1	60.1	62.35	-3.11

FEV1 in % of the norm is shown for each patient at 0, 3 and 6 months of the study.

Table 2. Lung function.

characteristics of the disease, the health and the physical fitness of patients was very variable during the study period mainly due to intercurrent infections. Three patients had suffered from vertebral fractures before the study (data not shown); they were all among the patients that completed the study. Three patients had to withdraw from the study. Their FEV1(%) was 27, 26 and 25 and their trabecular density at the spine as measured by QCT was 99.6 mg/cm^3, 159.4 mg/cm^3 and 85.1 mg/cm^3, respectively.

Safety

The training was generally well tolerated. No significant drop in blood pressure or oxygen saturation was observed in any of the patients with regular cardiopulmonary monitoring during or after the training. Three of the patients had to withdraw from the study. One patient finished training after four weeks as he experienced discomfort in his head with the vibrations. One patient was recommended by the study investigator to finish after six weeks as he did not perform the training regularly due to time limitations. One patient had to stop training due to a new thrombosis of the superior vena cava. This patient was carrying an intravenous port device and had a previous history of venous thrombosis of the subclavian vene. At study entry no recent thrombosis or significant vessel stenosis were detected by ultrasound in this patient. After three months of the study, the patient experienced a sudden onset swelling of the anterior neck and ultrasound showed a thrombus in the superior vena cava, which

	2-leg jump change				**1-leg jump change**	**Tibia muscle CSA change**
Patient No.	**Force [%]**	**Power [%]**	**Veloc. [%]**	**Height [%]**	**Force [%]**	**CSA[%]**
1	5.2	1.9	-0.1	2.3	20.6	0.0
2	-26.2	-7.9	7.1	-25.1	3.9	12.8
3	-20.5	-16.4	-0.9	-4.5	-8.5	-5.0
4	12.1	49.1	24.5	46.4	9.4	11.7
5	-13.8	7.5	12.9	23.1	-7.9	8.8
6	17.9	74.5	48.3	63.9	19.9	11.5
7	12.0	16.5	5.6	5.8	1.2	2.2
8	-31.0	-10.9	6.2	6.4	24.3	-5.3
Median (range)	**-4.3** (-31.0–17.9)	**4.7** (-16.4–74.5)	**6.6** (-0.9–48.3)	**6.1** (-25.1–63.9)	**6.7** (-8.5–24.3)	**5.5** (-5.3–12.8)

Force, power, velocity and jump height were assessed on the Leonardo plate using a standardized two-leg jump. In addition, maximum force was also assessed using the one leg jump. Results are expressed as percentage change of the individual patient's performance at the end of the study period in relation to the first assessment as well as the median of all patient results. In the last column, percentage change of muscle cross-sectional area as assessed by pQCT measurements is shown.

Table 3. Mechanography 2-leg jump, 1-leg jump and tibia muscle cross-sectional area.

had not been demonstrated in previous examinations. The patient was therefore withdrawn from the study. One patient, who had previously suffered from CF arthropathy, developed joint effusions of the knees but continued his training with subsequent resolution of the effusions (Table 1). Patient 3 had a manifestation of diabetes mellitus during the study period. Patient 8's lung function deteriorated significantly during the study period resulting in high urgency listing for lung transplantation. No other serious adverse events were found. None of the patients developed persistent arthralgias or arthropathy (the arthritis in the patient mentioned above resolved completely while still participating in the study) and no new vertebral fractures were detected on VFA.

Range of motion

As a surrogate for muscle stiffness, the mobility of the vertebral column was assessed using the finger-floor distance. The median improvement in finger floor distance in those patients with a finger-floor distance >0 cm at the beginning of the study was 13 cm (data not shown).

Lung function

Results for parameters of lung function are shown in Table 2. There was a broad range of FEV1 in our study population. The median FEV 1 [% of norm] was 62 (range 27-108). No consistent changes were observed for parameters of lung function during the study period.

Bone densitometry and mechanography

As shown in Table 3 for the two-leg jump and in Table 4 for the trunk bend, the main change in most patients was an increase in muscle power with an increase in velocity and jump height. This indicates an increase in efficiency with less force necessary to generate the same or more power. Peak forces as assessed in the one-leg jump also increased in the majority of patients. These changes did not always correspond directly to changes in muscle cross-sectional area as assessed in the pQCT measurements (Table 3). In Figure 1, the changes in power per kg for each patient are depicted for each visit. Patients starting with low power increased most whereas patients with high power at study entry maintained or decreased their abilities to generate muscle power. Most increases were seen early in the study period. Trabecular bone density as measured at the spine, the distal radius and the distal tibia are shown in Table 5. There were no consistent changes that would correspond to changes in muscle force or power over the study period. No changes were observed in geometric parameters of bone at the radius or tibia (data not shown).

Discussion

Whole body vibration with the Galileo^{TM} was well-tolerated in three-quarters of the study population. Among those who completed the study, two patients were post-lung transplantation. The significant disease-associated co-morbidity might nevertheless lead to a higher rate of adverse events

	Change trunk bend [change]			Change QCT spine
Patient no.	Force change [%]	Power change [%]	Velocity change [%]	Trab. density change [%]
1	0.63	12.28	9.95	0.90
2	-10.59	-18.69	-18.60	1.51
3	-11.19	-27.02	-21.34	1.90
4	5.92	26.79	23.39	-8.57
5	7.22	8.21	3.89	1.71
6	41.80	127.98	99.32	20.19
7	3.51	2.56	1.85	-7.11
8	11.38	13.01	8.90	-0.08
Median	4.72	10.25	6.40	1.20

Force, power and velocity were assessed on the Leonardo plate using a trunk bend. Results are expressed as percentage change of the individual patient's performance at the end of the study period in relation to the first assessment as well as the median of all patients' results. In the last column, percent change of trabecular density of the spine as assessed by QCT measurements is shown.

Table 4. Mechanography trunk bend and QCT spine.

Patient no.	QCT spine [mg/cm^3]		QCT spine change	pQCT radius change	pQCT tibia change
	Start	Stop	[%]	[%]	[%]
1	166.1	167.6	0.90	1.51	0.54
2	166.0	168.5	1.51	0.58	0.19
3	136.5	139.1	1.90	1.28	-0.96
4	64.2	58.7	-8.57	-12.35	-9.19
5	175.8	178.8	1.71	-4.09	-0.14
6	61.9	74.4	20.19	-3.73	4.72
7	153.3	142.4	-7.11	3.16	-0.24
8	129.2	129.1	-0.08	7.47	0.12

Results for trabecular density at the spine, distal radius and distal tibia are shown.

Table 5. Bone densitometry.

and training intolerance than in other patients or volunteers. Several of these adverse events (thrombosis in one patient, arthritis in another patient) were not interpreted as related to the intervention. The occurrence and disappearance of the arthritis in one patient with continued training might support this view for the arthropathy.

Power, velocity and jumping height increased in the majority of patients. As shown in Table 4, similar improvements were also observed in the trunk bend, which is especially important for this patient group. A strong variation in response to the training was seen. This might be due to the fact that a broad spectrum of disease severity and level of neuromuscular function was represented among the patients included in the study and all of them were submitted to a similar training regimen. As illustrated in Figure 1 there was no increase in muscle power in those patients who started training with high values for muscle power. In the patients starting with low muscle power, increases were substantial. Most patients in this study did also show an increase of peak force in the one-leg jump. Patients 4 and 6, who improved most, were the two patients post-lung transplantation. Even though both patients had attended regular physiotherapy up to three times a week before, neuromuscular function was impaired and they both showed improvements which also translated into better daily functional abilities as reported by the patients.

It is tempting to speculate that a major effect of the training in our study was an improvement in neuro- and intramuscular co-ordination, as less force was necessary to generate the same or an increased power. This is further supported by the finding that changes in force and power did not necessarily correspond to changes in muscle cross-sectional

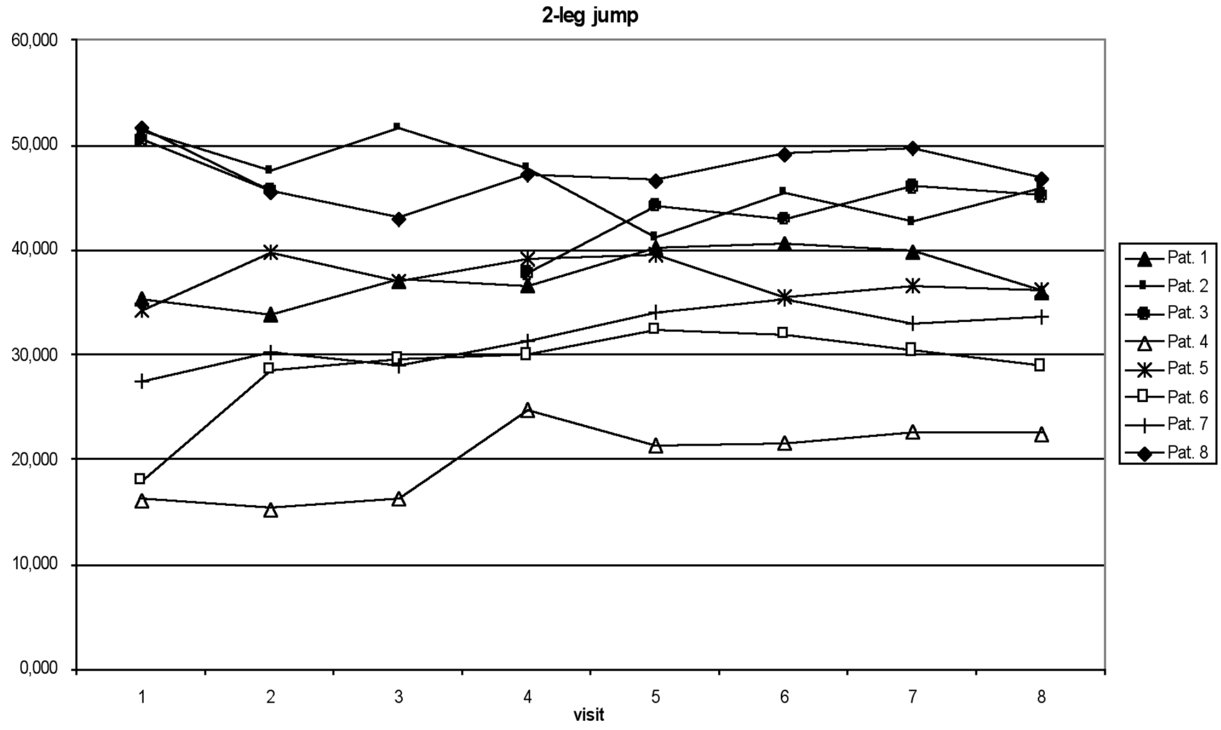

Figure 1. Muscle power per kg body weight assessed in the two-leg jump is shown for each patient at each study visit.

area, although several patients clearly increased their muscle cross-sectional area (Table 3). Some patients may have increased their force and power without an increase of muscle mass by better neuromuscular and intramuscular co-ordination.

Even though there was a progressive increase in amplitude and frequency of the training together with subsequent introduction of additional weights, most increases were observed during the first weeks of training and then remained on a rather steady level. This might lead to two conclusions: first, a training period of three months might be sufficient to substantially improve many patients; and second, for a steadier and continuous increase in muscle power and velocity, a training programme with further increases in frequency and/or additional weights have to be used. These questions were not subject to the present pilot study but will have to be addressed in further intervention studies. Another problem of this study was the lack of a control group to clearly demonstrate the effects of the Galileo™ training in contrast to changes in muscle force and power due to other reasons. This again will have to be addressed in larger, controlled studies. It can nevertheless be concluded from previous studies[22] that, at least with regard to the two-leg jump, no significant improvements due to learning effects on the test procedure can be expected.

In our study, no consistent changes were observed in parameters of lung function, a problem that has been encountered in many studies in CF as, due to the large intraindividual variations, consistent changes will only be observed during much longer study periods.

Neither trabecular density in the spine nor parameters of bone density and geometry at the radius and tibia showed consistent changes, which may be due to the study period of six months. Within a short period of time, both the co-efficient of variation of measurements as well as the delay in measurable effects on bone, which follow increases in muscle mass and force by several months, might have been responsible. The increase in peak force observed in our study might nevertheless be important for maintaining or increasing bone mass in cystic fibrosis patients[6]. A relatively high percentage of patients had a normal trabecular density at the spine (Table 5) and also normal values for cortical and trabecular parameters on pQCT measurements (data not shown). In these patients, no further increases can be expected. Other intervention studies in healthy volunteers[23,24] did not reveal any increase in bone mass despite an increase in muscle power and force either. In contrast, interventions in post-menopausal women did show an increase of bone mass at the hip[25] and a study using a different vibration device on children with various neuromuscular disorders showed significant increases in trabecular density at the spine[26]. It has to be noted though that patients in the latter study started at low levels of trabecular density and therefore an increase of 10% does not represent a strong increase in absolute bone mass.

Altogether we conclude that whole body vibration with the Galileo^{TM} is a promising new technique to improve muscle power and to a certain extent force in patients with cystic fibrosis. The advantage is that the amount of time that has to be spent for the training is fairly minimal. For future studies, a focus on specific end-points in a controlled study design will be necessary and these will include the question of persistence of positive training effects, the documentation of preservation or improvements in bone mass, prevention of kyphoscoliosis and the role of the training as an adjunct to the management of pre-, peri- and post-lung transplantation patients.

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