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ORIGINAL ARTICLE

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The effects of 11 weeks whole body vibration training on jump height, contractile properties and activation of human knee extensors

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Abstract The purpose of the present study was to investigate whether 11 weeks of whole body vibration (WBV) training applied in a way that is commonly seen in practice, i.e. without additional loads, would improve muscle activation and/or contractile properties of the knee extensor muscles and counter movement jump height in healthy subjects. Ten subjects belonging to the experimental group trained three times a week and stood bare-foot with a 110 ° knee angle on a vibration platform (30 Hz, 8 mm amplitude). They underwent five to eight sets of 1-min vibration with 1 min rest in between. Ten control subjects followed the same training programme but stood (110 ° knee angle) beside the platform. Before, during and following the training period the subjects were tested. Values [mean (SEM)] obtained in the last test were expressed as percentages of the baseline value and presented for control and experimental groups. Quadriceps femoris isometric muscle force [105.4 (6.2)%, 99.9 (2.0)%; $P = 0.69$], voluntary activation [107.1 (6.0)%, 101.1 (2.3)%; $P = 0.55$] and maximal rate of voluntary force rise [95.4 (6.0)%, 103.3 (7.7)%; $P = 0.57$] did not improve. The maximal rate of force rise during electrical stimulation was increased [102.3 (4.5)%, 123.6 (7.5)%; $P = 0.02$]. Counter movement jump height was not affected by WBV [103.7 (1.8)%, 103.0 (2.8)%; $P = 0.71$]. In conclusion, 11 weeks of standard two-legged WBV training without additional training loads did not improve functional knee extensor muscle strength in healthy young subjects.

Keywords Electrical stimulation · Voluntary activation · Maximal rate of force rise

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Introduction

Over the last few years there has been a great increase in the use of whole body vibrating platforms as a training device for (recreational) athletes, elderly people and patients. Companies that produce the platforms advertise that whole body vibration (WBV) can be used to increase athletic power, to treat muscle atrophy and they even suggest that WBV would be beneficial for people with multiple sclerosis. However, the scientific evidence available to support these types of claims is very sparse. Ten days WBV exercise has been shown to increase maximal jump height (Bosco et al. 1998). In addition, following just a single WBV training session, leg extensor muscle power (Bosco et al. 1999, 2000) and counter movement jump height increased (Bosco et al. 2000), although a decrease in jump performance has also been found following a single training session (Rittweger et al. 2000). More recently Torvinen et al. (2002a) found a 3.2% increase of isometric knee extensor strength and a 15.7% improvement in body balance in young healthy subjects following a single 4-min WBV bout. However, the same authors found no improvement of body balance and isometric knee extensor strength following 4 months of WBV training (Torvinen et al. 2002b). These latter findings suggest that the long-term effects of WBV training may be insignificant. However, in the same study, jump height increased by 8.5% (Torvinen et al. 2002b). To date the latter study is the only one in which long-term effects of WBV training have been investigated and the mechanism(s) underlying the effects of WBV training remain unclear.

It has been suggested that the effects of WBV on muscle performance are elicited via reflex muscle activation (Rittweger et al. 2000) leading to "neurogenic adaptation" (Bosco et al. 1999, 2000). Indeed skeletal muscle can be forced into a contraction by prolonged percutaneous mechanical vibration of the muscle belly or, more commonly, the distal tendons (Desmedt and Godaux 1978). This so-called tonic vibration reflex is mainly induced through activation of the primary muscle spindle (Ia) fibres (Roll et al. 1989). However, it is questionable whether substantial vibration-induced muscle activation occurs during WBV. Firstly, only moderate increases of oxygen uptake (Rittweger et al. 2001) and leg muscle surface EMG (unpublished observations) have been found during WBV. Secondly, both agonist and antagonist muscles are simultaneously exposed to the vibration stimulus during WBV, which may further enhance the inhibitory effects of vibration (Martin et al. 1986).

Nevertheless, the reported short-term positive effects of WBV on leg muscle power output (Bosco et al. 1998, 1999, 2000) and the fact that vibration platforms are widely used as training devices not only by elite athletes, but also by recreational athletes, patients and elderly people, warrants a study on longer-term training effects of WBV. Therefore, the goal of the present study was to investigate whether 11 weeks WBV training would improve knee extensor muscle activation and contractile properties in healthy subjects. We decided to investigate the effect of two-legged WBV training without additional training loads, since this is the way that WBV training is applied in practice by the majority of users. Moreover, in studies that have reported positive effects of WBV, no additional training loads were used (Bosco et al. 1998, 1999, 2000; Torvinen et al. 2002a, b).

Methods

Subjects

Twenty healthy, physically active, students were assigned to either the control group [four female, six male; age 19.9 (0.6) years; mean (SEM)] or the experimental group (four female, six male, 20.7 (0.5) years). In addition to gender, the groups were matched for maximal voluntary isometric contractile force (MVC) of the knee extensors and the ability of the subjects to voluntarily activate their muscles. The latter was established during two pre-tests before the training period with the use of superimposed electrical stimulation (see below). The local ethics committee approved the study and all subjects took part after providing informed consent.

Vibration procedure and training

The effects of 11 weeks WBV training were investigated. During the first 3 training weeks subjects trained three times a week. During each session they underwent five sets of 1-min WBV (1 min of seated rest in between). Subjects of the experimental group stood with bare feet and a 110 ° knee angle on a Galileo 2000 (Novotec, Germany) vibration platform, which vibrated at 30 Hz with 8 mm amplitude. The subjects of the control group followed the same training programme under the same conditions, except that they did not experience vibration. Subjects of both groups carefully maintained the 110 ° knee angle during the training sets. Over the weeks, training volume was gradually increased from five to eight sets per training session (Table 1).

Please note that WBV training, especially by some of the elite athletes, is used in a number of different ways, which includes one-legged training and squatting exercises sometimes with additional training loads. However, the great majority of users including many competitive athletes apply WBV training in a similar way to that used in the present study; this method was also chosen by Bosco et al. (1998, 1999, 2000) and Torvinen et al. (2002a,b).

Table 1 The training programme. There were 11 weeks during which subjects trained three times a week. The number of 1-min sets was gradually increased from five (weeks 0–2) to eight during the last 2 weeks (11 and 12). There was always 1 min of seated rest between sets

Training week	Cumulative training number	Programme
0, 1, 2	1–9	5×1 min
3, 4	10–15	6×1 min
5, 6	No training	
7	16–18	6×1 min
8, 9, 10	19–27	7×1 min
11, 12	28–33	8×1 min
13	No training	

Test days

Subjects were tested on five different occasions (see arrows in Fig. 1). In addition, prior to the actual baseline measurement (week 0) subjects were tested two times to eliminate learning effects. To monitor training effects that would only manifest themselves following a period of (relative) rest, as is believed to occur by many sports coaches, two periods (weeks 5 and 6 and week 13) without (vibration) training were incorporated into the programme. Subjects were also tested just before and then immediately after (weeks 7 and 14) these periods without WBV training. Testing prior to weeks 5 and 13 took place 24–48 h following the last preceding training session.

Tests

Jump height

Maximal jump height was assessed with a tape measure, which was attached to a girdle around the subjects' waist and run down through a narrow opening in a large wooden floorboard. The tape measure was pulled straight when the subjects were standing in the upright position with their feet on footprints (shoulder width) marked on the floorboard. Subjects were instructed to jump as high as possible following a counter movement from the upright position and to land on the footprints: only vertical jumps were allowed. The distance that the tape measure was pulled through the floorboard during the jump was taken as a measure of the jump height. If the last attempt exceeded the best of the preceding

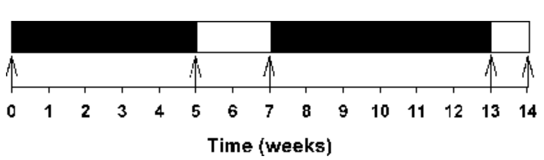

Fig. 1 Test days. The *arrows* indicate the five test occasions. Baseline values were obtained just prior to week 0. A 2-week non-training period (weeks 5 and 6) separated two periods of training (weeks 0–4 and 7–12) and there was a further non-training week during week 13, before the final test

attempts by 1 cm or more, subjects had to jump again, with a minimum of three and a maximum of six attempts, with 1 min rest in between. Although, this measure of jump height is very simple, in pilot experiments the within subject variation was found to be small relative to the variation among the subjects ($n = 10$) when measurements were made on 2 different days (intra class correlation coefficient = 0.98, with 1.00 being the maximum). This means that even with a relative small sample size an improvement of only a few per cent would be detectable.

Contractile properties

All contractile properties were investigated during bi-lateral tasks. This was carried out to make our test more sensitive for detection of training effects related to improvement of voluntary activation. Recently we have found that the capacity for voluntary activation is lower during bi-lateral compared with uni-lateral tasks, particularly during explosive leg extensions (Van Dieën et al. 2003). Therefore it was anticipated that an improvement of voluntary activation would manifest itself more clearly during two-legged compared with one-legged tasks.

Contractile properties of the knee extensors of both legs were investigated following fixation of the subjects' hips and shoulders on a rigid chair with hip and knee angles set at 90 °. Knee extensor forces were measured at the shins, which were strapped to transducers placed 27 cm distally from the knee joints. Constant current electrical stimulation (200 μs pulses) was applied using a computer-controlled stimulator (model DS7, Digitimer Ltd., Welwyn Garden City, UK) and two pairs of self-adhesive surface electrodes (8 × 13 cm, Schwa-medico, 283100, The Netherlands) placed transversely over upper and lower thighs. Current strength was increased until 50% of MVC was produced during 700 ms tetanic (150 Hz) stimulation (de Haan et al. 2000).

MVC was obtained from the attempt, which resulted in highest summed force value of both legs during 2 s of isometric contractions. If the MVC of the last attempt exceeded the best of the preceding attempts by 2% or more, subjects had to perform another MVC, with a minimum of three and a maximum of six attempts. Unless otherwise indicated, there was always 3 min rest between attempts.

The determination of the MVC was followed by the assessment of the maximal force generating capacity of the muscles (MFGC). The MFGC is the maximal isometric force expected when a subject is able to voluntarily activate all muscle fibres maximally. MFGC was determined as follows: a short 80-ms tetanic train (300 Hz) was applied to the resting muscles, followed by superimposition on a MVC. The amount of extra electrically evoked force on top of the voluntary force traces was expressed as a percentage of the force obtained when the 80-ms train was applied to the resting muscles. This value was subsequently subtracted from 100%, resulting in a measure of voluntary activation (de Haan et al. 2000). MFGC was calculated using the following formula: MFGC = (MVC/voluntary activation)×100% (de Ruiter et al. 2000).

MFGC was calculated from the attempt (out of three) with the highest summed voluntary forces of both legs immediately prior to the superimposed stimulation.

Subsequently maximal tetanic (700 ms, 150 Hz stimulation) force was obtained. This was followed by determination of the stimulated maximal rate of force rise (SMRFR) from three 80-ms pulse trains (300 Hz, 3 s in between). SMRFR was taken as the maximum of the positive filtered (30 Hz filter frequency) differentiated force signals of the fastest contractions and, to correct for activated muscle mass, expressed as a percentage of maximal tetanic force of each leg (percentage tetanic force × metres per second). From the best attempt the values of both legs were subsequently averaged.

Voluntary maximal rate of force rise (VMRFR) was obtained from three to six attempts (duration < 500 ms) during which the subject was encouraged to contract the knee extensors as fast as possible from a fully relaxed state to over 80% of MVC values. VMRFR was taken from the attempt that resulted in the highest summed value of both legs. Subsequently VMRFR was expressed as a percentage of the MFGC of each leg (percentage MFGC × metres per second). Using the best attempt, the values of both legs were subsequently averaged.

Statistics

The results are presented as mean values (SEM). ANOVA repeated measures were used to test for significant differences between the groups ($P < 0.05$). On significance of the main effects, simple contrasts were used to locate the differences.

Results

One subject dropped out following 2 weeks of WBV training because she developed shin pains during WBV. The results of this subject have been removed.

As expected, since the groups were matched for maximal isometric force production, baseline values (week 0) were similar ($P > 0.05$) for both groups (Table 2).

WBV training did not ($P = 0.69$) increase MVC (Fig. 2A) or MFGC ($P = 0.55$; Fig. 2B) of the knee extensor muscles. There was a tendency ($P = 0.07$) for a faster SMRFR in the WBV group at weeks 7 and 13 (Fig. 2C), and during the last test (week 14) the difference between the groups reached the level of significance ($P = 0.02$). However, this increased rate of SMRFR was not accompanied by an increase in the VMRFF ($P = 0.57$; Fig. 2D). There was a tendency ($P = 0.07$) for jump height to increase, but this tendency was present to an equal extent ($P = 0.71$) in both groups (Fig. 2E), indicating that application of WBV during training did not improve jump height.

Discussion

The present results indicate that 11 weeks of standard two-legged WBV training do not improve functional strength of the knee extensors. Although thus far the influence of long(er)-term WBV training has been investigated in one study only, the present results partially deviate from that study (Torvinen et al. 2002b) and are certainly not in-line with studies on the short-term

Table 2 Baseline values of the parameters. Mean baseline (week 0) values (SEM) are presented for maximal voluntary isometric contractile force of the knee extensors (*MVC*), maximal force generating capacity (*MFGC*), the maximal rates of electrically stimulated (*SMRFR*) and voluntary force rise (*VMRFR*) and counter movement jump height. *WBV* Whole body vibration. There were no significant differences between groups

	Control group	WBV group
MVC (kN)	1.70 (0.13)	1.62 (0.16)
MFGC (kN)	1.77 (0.13)	1.54 (0.15)
SMRFR (% m s^{-1})	1.75 (0.10)	1.65 (0.15)
VMRFR (% m s^{-1})	0.78 (0.06)	0.81 (0.07)
Jump height (m)	0.59 (0.03)	0.57 (0.05)

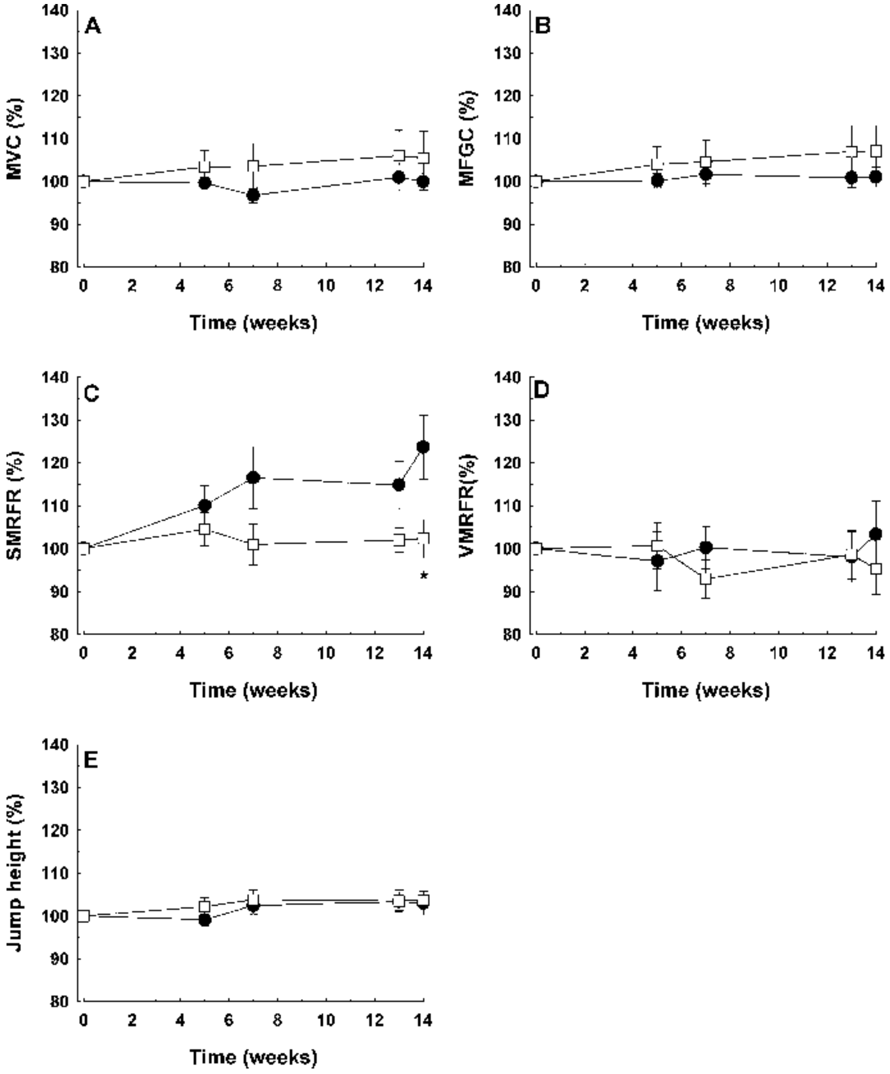

Fig. 2A–E The effect of whole body vibration (WBV) training on knee extensor performance. Functional parameters [means (SEM)] as a function of time (*x*-axis), normalised to the baseline values obtained just prior to week 0 (100%). Maximal isometric contraction force (*MVC* in **A**), maximal force generating capacity (*MFGC* in **B**), maximal rates of electrically stimulated (*SMRFR* in **C**) and voluntary force rise (*VMRFR* in **D**) and counter movement jump height (**E**), for the control (open squares, $n=10$) and the WBV group (closed circles, $n=9$). *Significant difference between groups

effects of WBV training (Bosco et al. 1998, 1999, 2000; Torvinen et al. 2002a). The latter studies reported increased isometric leg extension strength (Torvinen et al. 2002a), power and jump height (Bosco et al. 1999, 2000) following a single training session and also after 10 days of training (Bosco et al. 1998). Isometric knee extensor strength did not improve following 4 months of WBV training (Torvinen et al. 2002b). Others have found positive effects of vibration training on muscle force (Issurin and Tenenbaum 1999). However, in the latter study the vibration was superimposed on a training load, which is completely different from how WBV was used in the other studies and is applied in practice, where not only patients and elderly people, but also most recreational and competitive athletes, stand on the vibration platform in a half-squatted position without additional loads.

Although we could not demonstrate any benefits of WBV training on the functional contractile parameters of the leg extensors, a potential point of concern in the present study was the relatively small sample size ($n=10$). Post hoc analysis of our data showed that we would have been able to detect training effects in the order of 5–9% for jump height, MFGC and MVC. However, changes in SMRFR and VMRFR would only have reached statistical significance if they were greater than 15% (which in fact was the case, see Fig. 2C) and 22% respectively. Although the within-subject variation is unavoidable with these kinds of measurements, it may be argued that the present study was under-powered to detect relatively small, but perhaps functionally relevant, changes in some of the parameters. However, with the exception of SMRFR, which did improve significantly, none of the other parameters tended ($P>0.55$) to increase more in the WBV group compared with the control group. If anything, mean values were often lower in the WBV group (Fig. 2). Therefore, it is highly unlikely that a larger sample size would have led to a different outcome. Nevertheless, it is surprising that particularly for our most sensitive parameter (jump height) we were unable to reproduce the findings of Torvinen et al. (2002b) who reported improvements of jump height of 10.2% and 8.4% respectively after 2 and 4 months of WBV. However, in the latter study, young and healthy subjects performed very light exercise (without additional loads) during WBV, although the authors themselves state that "it was very unlikely that these light exercises were behind the clear rise in the jump height" (Torvinen et al. 2002b). Perhaps more importantly, and in contrast to the present study, the training of the subjects in the study of Torvinen et al. (2002b) was carried out unsupervised and the subjects in their control group did not perform any exercise at all. In the present study the second and third authors (S.M. van Raak and J.V. Schilperoort) strictly supervised all training sessions and the control subjects did the same amount of training (without the vibration) as the vibration group.

As indicated above, the only effect of WBV training in the present study was a 15–21% increase in the SMRFR. This was an unexpected finding because we anticipated that any possible effects of 11-week WBV training would mainly be of neural origin and therefore would manifest themselves primarily during voluntary tasks and not during electrical stimulation. We have no satisfactory explanation for the increased SMRFR. Improved activation can be ruled out, as activation was always maximal during electrical stimulation with a 300-Hz frequency. Increased contractile speed and/or stiffness of the muscle tendon complex are also highly unlikely to account for the improved SMRFR; if this had occurred, at least a tendency for the VMRFR to increase in parallel with SMRFR would have been expected and this clearly was not the case. Finally, a reduction of antagonistic co-contraction during electrical stimulation could result in increased knee extensor contractile speed. Although we did not measure EMG of the hamstring muscles in the present study, we have no indications for co-activation of the hamstrings during electrical activation of the knee extensors in otherwise fully relaxed subjects.

Although the finding of an increased SMRFR remains puzzling, it clearly was not accompanied by improvement of functional parameters such as MVC, VMRFR and jump height. The tendency for an increased jump height in both groups probably reflects that learning (which caused significant increases in jump height during the two pre-tests, data not shown) still played a role during the tests performed just before and immediately after weeks 5 and 6 (Fig. 2E).

VMRFR is an important parameter, because it reflects the capacity of subjects to activate their muscles in a very short time, which is important during power tasks such as jumping. Van Cutsem et al. (1998) have recently shown that initial motor unit firing rates and the rate of force rise improved in parallel following conventional explosive strength training of tibialis anterior muscle. Baseline VMRFR was only half of what the muscle was capable of during maximal electrical activation as indicated by SMRFR (Table 2). This illustrates that even without a direct effect on the muscle's properties, WBV training, just by increasing voluntary activation, could have enhanced VMRFR. However, the present data did not show any effect of WBV training on VMRFR (Fig. 2D).

There are a number of considerations that may explain why standard two-legged WBV training without additional training loads fails to improve functional muscle strength. Although, prolonged Ia afferent discharge has been shown to excite, via both mono- and polysynaptic pathways (Romaiguere et al. 1991), homonymous motoneurons leading to contraction of the muscle (Desmedt and Godaux 1978), the force increases in response to direct muscle tendon vibration are rather low (Bongiovanni and Hagbarth 1990). Vibration-induced force increases are probably limited because vibration also elicits a certain level of presynaptic Ia inhibition, which brakes the further recruitment of motoneurons (Desmedt and Godaux 1978). Moreover, during vibration the recruitment of motoneurons is in accordance with the size principle (Desmedt and Godaux 1978) and consequently also during WBV any recruitment of motoneurons may be limited to the smaller ones. The findings of Rittweger et al. (2001) indirectly indicate that fibre recruitment during WBV is limited. They found an increase in oxygen uptake of only 4.5 ml min^{-1} kg^{-1} when WBV was imposed during stance in squatted position, bringing oxygen uptake to the level of "moderate walking". Even during squat exercise with additional loads (35–40% of the body weight) WBV caused a similar increase in oxygen uptake (about 4.5 ml min^{-1} kg^{-1}) compared with when the same squat exercise was performed without vibration (Rittweger et al. 2001). This finding suggests that WBV-induced fibre recruitment is also limited at higher training loads. In addition, it is important to note that during WBV the vibration is not applied directly on the muscle tendons, but usually on the soles of the feet with each joint having a dampening effect on the vibration stimulus in the distal to proximal direction of the leg. Moreover, vibration causes reciprocal inhibition of the antagonist muscles and, during WBV of several leg muscles, both agonists and antagonists are simultaneously exposed to the vibration stimulus, which makes the net outcome with respect to muscle activation hard to predict. Furthermore, simultaneous vibration of more muscles may enhance the inhibitory effects of vibration (Martin et al. 1986).

Based on the above considerations the most likely explanation for the lack of training effects of WBV, which was applied in a way that is most commonly seen among users in the field, is that training intensity is probably not high enough to induce any change in the contractile properties of the muscle. The larger motor units in particular may not have been recruited at all during this kind of WBV. The fact that a single WBV training causes only moderate muscle fatigue (De Ruiter et al. 2003; Rittweger et al. 2000) and the observation (unpublished) that leg muscle surface EMG increased upon WBV, but that values only reached 10–50% of maximum values, support the notion that fibre recruitment due to WBV is limited. Nevertheless one may argue that there still may be some kind of "neurogenic adaptation" (Bosco et al. 1999) in response to WBV training, which would not necessarily have to affect the properties of the muscle. However, the present results do not support this idea since WBV training did not enhance performance during voluntary (fast) muscle contractions.

In conclusion, although the SMRFR significantly increased during 11 weeks of standard WBV training, MVC, VMRFF and counter movement jump height were unaffected. Based on these results standard WBV training does not seem to be an effective method for increasing maximal muscle force, rate of force development and jump height in healthy young subjects.

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