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ABSTRACT

While bones and muscles adapt to mechanical loading, it appears that very specific types of stimuli must be applied to achieve osteogenesis. Our study assessed musculoskeletal outcomes to 30 training sessions on an Inertial Exercise Trainer (Newnan, GA). Subjects (n = 13) performed workouts with their left leg, while their right served as an untreated control. Workouts entailed three 60-s sets each of knee extension, hip extension and calf press exercises, separated by 90-s rests. Before and after the 30 training sessions, subjects underwent strength tests (knee and ankle extensors of both legs), DEXA scans (hip, knee and ankles of both legs), and blood draws. After 30 training sessions 2 × 2 ANOVAs showed left leg peak torques rose significantly. 2 × 2 ANCOVAs, with bone scan area as a covariate, showed significant left leg calcaneal bone mineral content (+ 29 %) and density (+ 33 %) increases after 30 training sessions. A significant decline in C-terminal telopeptides of type I collagen, a blood marker of bone resorption, also occurred after 30 training sessions. The Inertial Exercise Trainer's large volume of training session repetitions elicited high peak force, peak acceleration and impulses that likely provided a mechanical loading stimulus that evoked calcaneal accretion.

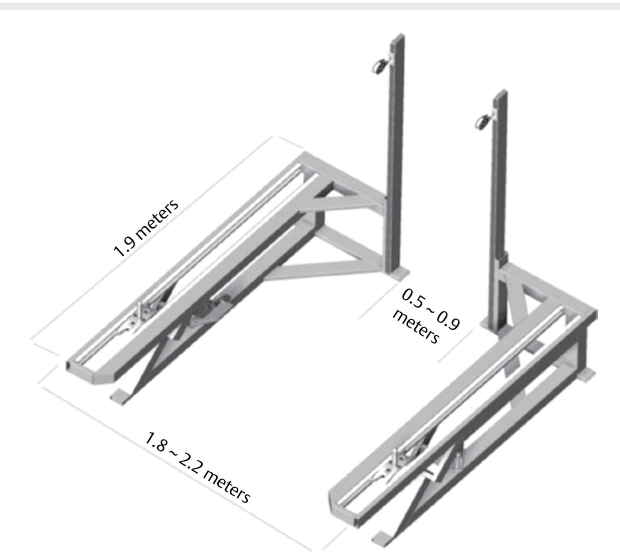
Introduction

Bone and muscle adapt to the types of exercise stimuli imposed. Exercise to enhance musculoskeletal fitness seeks concurrent bone and muscle improvements. Intuitively, this appears to be a reasonable goal, since as muscles accelerate and decelerate body segments to oppose the pull of gravity, bones adapt in accordance with the forces exerted [1, 4, 14–16]. Yet while muscle's plasticity allows it to adapt to various loading paradigms, bone is far less responsive [3, 20, 34, 55]. This impacts the ability of resistive exercise to abate bone losses in disuse models (e. g. space flight, osteoporosis, geriatrics, etc.) [13, 15, 16, 57]. Unlike muscle, perhaps very specific stimuli must be applied over time to achieve osteogenesis [14, 23, 36, 47, 54]. Stimuli received by bones relate to the magnitude, frequency and rate of strain imparted [29, 37, 43]. Strain denotes changes in bone deformation relative to its initial length [14]. Magnitude is the extent of bone deformation, frequency is how often strain is imparted, while rate is the change in magnitude per second of deformation [14].

Osteocytes sense strains imparted by forces, and then convert mechanical loading stimuli into the commensurate bone adaptation [24, 33, 45]. Factors such as rate, frequency and magnitude all impact this process and, if one is neglected – whether by exercise equipment or program – bone growth may be impaired [14, 29, 42]. Bone growth begins once magnitudes exceed the osteogenic threshold [29, 42]. Yet some studies imply that rate is more important than magnitude [16, 47, 52]. Animal data showed that high-frequency loading evokes bone growth with as little as 100 με of magnitude applied at high rates [24, 29, 30]. Some studies also implied that once magnitudes exceed the osteogenic threshold growth is governed more by rate and frequency. Yet this is hard to say definitively, as few studies have measured all three factors [16, 28–30]. This may render even higher magnitudes unnecessary and reduce the need for heavy exercise loads.

While animal data must be interpreted cautiously due to their unique strain distribution patterns [31, 52], a mechanical loading model designed to optimally induce human bone growth should perhaps entail dynamic high-speed exercise [25, 28]. Unlike standard resistance exercise, high-speed activity with large impact forces and impulse loads may impart high strain rates, frequencies and magnitudes that elicit osteogenesis [4, 14, 17, 25, 28, 55]. Hardware that imparts such stimuli is rare. Yet one such device may do so without the caveat of gravitational resistance for operation. Called an Inertial Exercise Trainer (IET; Impulse Training Systems, Newnan GA), this device is equipped with a weight sled that oscillates on a low-friction track so repetitions occur at high rates of speed and acceleration. Since the track is parallel to the Earth's surface, forces required to move the sled do not include gravitational resistance. An IET illustration appears in ▶ **Fig. 1**.

Successive repetitions cause a rapid change in sled direction and offers impulse loads and impact forces at high rates and frequencies. The IET's novel operation, with lighter loads to permit high-speed movement, may benefit disuse models for which the heavy loads typically used for standard resistive exercise are impractical. Since it does not need gravity to operate, the IET may abate losses incurred during manned space flight, providing thus a disuse model for activity prone to musculoskeletal wasting [46, 47]. Unlike current in-flight resistive exercise devices, the IET conforms better to hardware requirements for manned spacecraft, as it has a low mass, area, power needs, and is easy to stow and operate [46, 47]. Prior IET research assessed data reproducibility, its relationships to anthropometry, and acute metabolic and hormonal changes to exercise [6, 7, 11, 12]. Yet chronic adaptations to the IET are unknown. Our purpose is to assess musculoskeletal outcomes from the IET. We hypothesize a chronic IET intervention will yield significant improvements in musculoskeletal physiology and performance.



▶ **Fig. 1** Overhead illustration of the IET.

Methods

Subjects

Before admittance, The University of Louisville's Institutional Review Board approved all procedures, and our study met this journal's ethical standards [26]. Subjects (mean ± sd: 29.4 ± 12 years; 2 men, 11 women) gave informed written consent, and filled out a medical questionnaire, prior to their participation. They were free of the following conditions: diabetes, asthma, hypertension, tachycardia, ischemia, arrhythmias, hyperthyroidism, and convulsive disorders. Female subjects of childbearing age were on birth control which, as evaluated by a recent meta-analysis, had an indeterminate impact on bone health [39]. Subjects were moderately fit (body fat percentage 26.9 ± 0.07; body mass 69.2 ± 9.9 kg), but none had trained on the IET. Thus prior to training sessions, they performed two familiarization sessions so IET repetitions were done correctly.

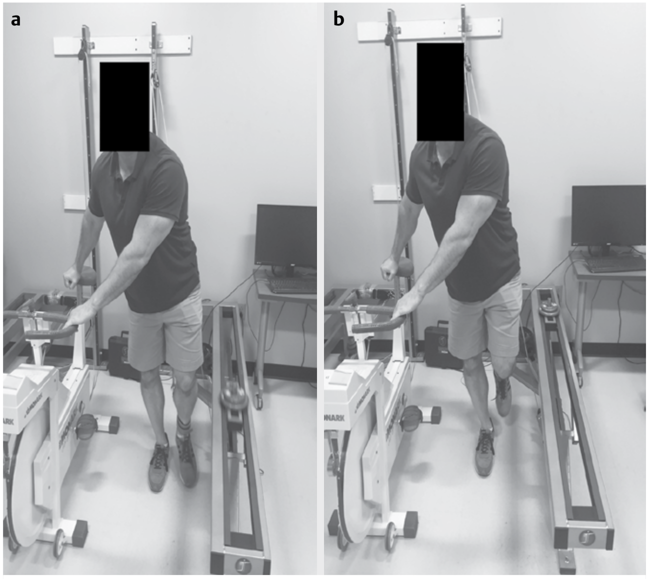
Study design

Subjects performed 30 training sessions on the IET. Before and after those sessions they underwent regional lower body DEXA scans and strength tests for both legs. Additionally, before and after the sessions they submitted to blood draws that were used to quantify markers of bone formation and resorption. To maintain the consistency of our study's procedures, we only exposed subject's left legs to our experimental treatment, meaning only that leg engaged in IET sessions. In contrast, their right leg served as a control condition and refrained from IET exercise. Subjects completed the 30 training sessions in 70 ± 6.3 days (range 58–84 days), or a rate of one every 2.3 days. The two familiarization sessions occurred at 11 ± 6.8 and 7 ± 5.4 days, respectively, prior to the first training session. Coinciding with the 10^{th}, 20^{th} and 28^{th} training sessions, subjects filled out self-administered 3-day dietary food logs to quantify nutrient intakes over time.

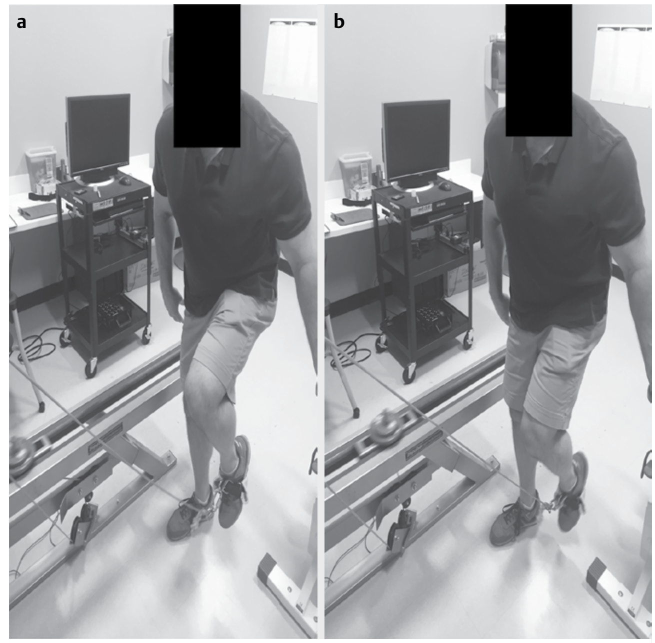
Familiarization sessions

Subjects practiced repetitions for the following exercises: knee extension, hip extension and seated calf press. Each was done with 3.4 kg of mass added to the 1.0 kg sled. For familiarization and training sessions, each exercise was done with subject's left legs. Knee extension occurred with a cuff around the distal shank. As the knee extended ~10–15° the sled traveled rapidly to the end of the track (▶ **Fig. 1**). As it traveled, the knee flexed back to its initial joint angle. Before the sled reached the end of the track the next repetition occurred, which then accelerated the sled to the opposite end of the track. Changes in sled direction created an impact force, which was high due to the sled's rate of movement [11]. As impact forces occurred, an impulse (force/time ratio) was generated. ▶ **Fig. 2a and b** depict the knee extension exercise.

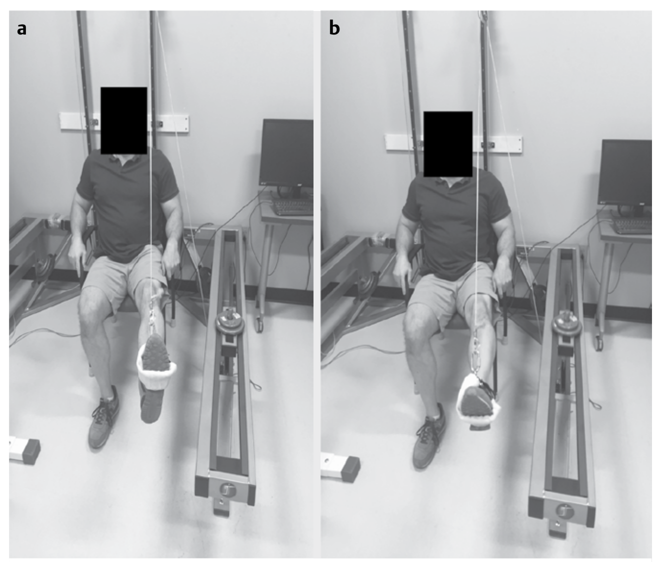
With a strap wrapped around the arch of subject's left foot, standing hip extension was done in a similar fashion. ▶ **Fig. 3a and b** depict hip extension repetitions. Unlike the knee and hip extension exercises, seated calf presses were done over a shorter range of motion. Given the limited sled displacement for the seated calf press, high rates of movement were more difficult to attain. For seated calf presses the strap was wrapped around the metatarsal



▶ **Fig. 2** **a** and **b**: Current study knee extension exercise done on the IET.



▶ **Fig. 3** **a** and **b**: Current study hip extension exercise done on the IET.



▶ **Fig. 4** **a** and **b**: Current study seated calf press exercise done on the IET.

heads of subjects' left feet. The intent of each IET exercise was to offer high amounts of axial loading. ▶ **Fig. 4a and b** depict seated calf presses.

Training sessions

Sessions began with a 5-min bilateral warm-up on a cycle ergometer (Ergotest, Stockholm Sweden) against one kilopond of resistance at a self-selected velocity, and then IET exercises were performed in the following sequence with subject's left leg: standing knee extension, standing hip extension and seated calf press. Per exercise, subjects performed three 60-s sets separated by 90-s rest periods. They were verbally encouraged to perform repetitions as rapidly as possible. Sessions were 25 min in duration. For each training session and exercise, we derived peak force (PF), peak acceleration (PA) and the impulse associated with the PF value. Due to the manner in which the IET equipment operates, PF represents the impact force imparted per repetition. Unlike standard resistive exercise, the IET is predicated on high-speed movement. So that subjects continued to achieve higher PA and impulse values throughout the 30 sessions, as well as to maximize the number of impact forces achieved with each set, the resistance (3.4 kg) added to the IET weight sled stayed constant throughout our study. We believe this kept strain rates and frequencies high, as heavier loads may limit osteogenesis by reducing strain rate and frequency [19, 28, 57].

DEXA scans

At 4 ± 2.1 days before and at 7 ± 2.0 days after, the 30 training sessions subjects underwent regional lower body DEXA scans (hips, knees, ankles of both legs). A radiologist performed scans with a calibrated densitometer (Hologic Discovery W; Marlborough, MA). DEXA scans exhibit higher precision than quantitative ultrasound and are the gold standard for bone morphology measurements [49]. Our scan procedures likely differed with many reported in the literature, but we were consistent and only compared our data within subjects with the same procedures. For ankle scans, subjects were oriented anatomically with respect to the densitometer to capture the medial surfaces as they lay supine, which was achieved by external hip rotation and 15° of knee flexion. Hip and knee scans were done while subjects maintained a standard supine posture. Otherwise the radiologist used standard procedures to operate and perform each DEXA scan. Pre- and post-intervention scans took 45 min. Our radiologist had eight prior years of experience in performing scans, and had a measurement intra-reliability < 2 %.

For DEXA data analyses, ankle scans were performed using the densitometer's forearm software, while knee scans were done with

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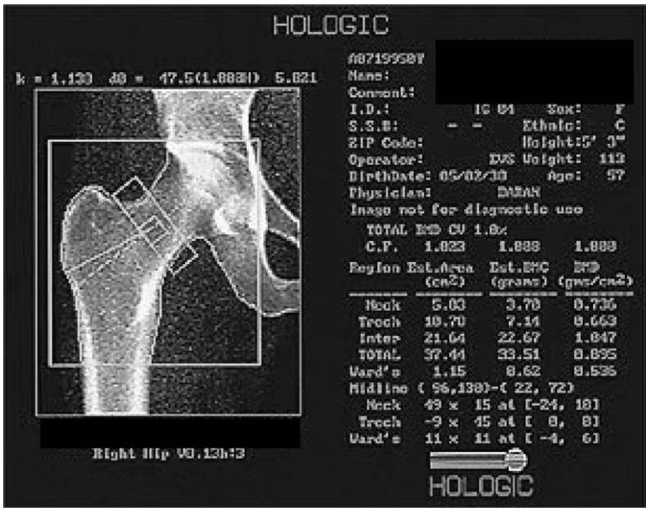


▶ **Fig. 5** DEXA scan image of the hip.

lumbar spine software. Otherwise, scans followed the same procedures. They included selection of the global region of interest option, followed by adjustment of the Toolbox's line mode in accordance with the scanned image. The computer's mouse was toggled to draw lines around bone segments to be analyzed. DEXA analyses then entailed selection of the Bone Map and MID/UD options, and concluded by selecting the Results option to derive bone mineral content (BMC), bone mineral density (BMD), and area values. Hip scan BMC, BMD and area values were derived for the femoral neck, greater trochanter, inter-trochanter, total hip and Ward's. For knee scans, we computed BMC, BMD and area for the distal femur (medial condyle and epicondyle) and proximal tibia (from the medial tibial plateau to its tuberosity). Ankle scan BMC, we derived BMD and area values for the calcaneus and distal tibia (medial malleolus). ▶ **Fig. 5** is a DEXA scan image of the hip.

Isokinetic strength tests

Left and right leg knee extensor strength tests, followed by those for the ankle extensors, occurred 4 ± 1.6 days before, and 4 ± 1.6 days after the 30 training sessions. Tests were performed at three (0, 1.62, and 4.86 rad· sec^{-1}) angular velocities. For each test, we aligned the subject's knee or ankle joint with the dynamometer's axis of rotation. For each subject, dynamometer (System 3 Biodex, Shirley NY) settings were held constant across test sessions, and velcro straps limited extraneous body movement. Tests began with five submaximal isometric contractions at 90° of knee flexion, separated by 30-s rest periods. After a 90-s rest, the isometric protocol was repeated with maximal contractions. They then performed the paradigm at 1.62, and then 4.86, rad· sec^{-1}. The ankle extensor protocol then commenced. With the dynamometer configured for ankle testing, repetitions occurred over a 45° range of motion, from a dorsi- to a full plantar-flexed position. Ankle isometrics occurred at a 0° (neutral) angle. Otherwise, its protocol was identical to that of the knee extensors. Peak torque and time to peak torque (PT, TTPT), derived from maximal contractions, were obtained per angular velocity.

Blood draws

Antecubital venous blood draws were carried out at 2 ± 1.6 days before and 3 ± 1.1 days prior to completion of the 30 training sessions. Aseptic techniques and universal precautions were used for blood draws, which were done by a licensed phlebotomist. Blood draws (~6 ml) occurred the morning after an overnight fast. Samples were placed in tubes (Reference # 367988; Vacutainer, Franklin Lakes NJ) and immediately stored at -80 ° C. Samples were shipped on ice to laboratory (Quest Diagnostics; Danville, IL) for analysis. Blood serum from samples were analyzed for procollagen type I intact N terminal propeptide (PINP) and C-terminal telopeptides of type I collagen (CTT), which are markers of bone formation and resorption, respectively. PINP is considered the most sensitive marker of bone formation [56]. All samples were measured in the same assay. Markers helped identify potential remodeling mechanisms from the IET intervention.

Food logs

To monitor dietary influences, subjects were given three 3-day self-reporting food logs during the 30-training session intervention. One of the three self-reported days occurred on a Saturday or Sunday. Subjects were instructed on how to fill out the logs, which included listing the quantities and types of foods eaten for three continuous days. Subjects were told to provide food labels to help quantify their nutrient intakes. Food logs were analyzed with software to quantify kilocalorie, protein and Ca^{+2} intakes over time.

Statistics

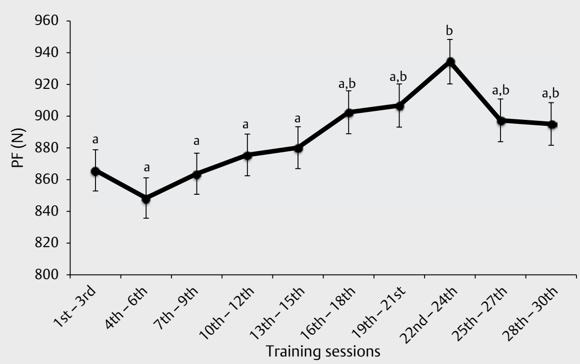
Our sample was based on a power analysis conducted prior to collection. Ten subjects would offer > 90 % power to detect a 15 % change from our training sessions with a two-factor repeated-measures design with leg and time as within-subject factors [22]. Thus our sample (n = 13) meets these power and change thresholds. Data were first examined for compliance to ANOVA assumptions (normality, independence, equal variances) and assessed with Z-scores to identify outliers. Per exercise, the degree of training progression for PF, PA, and the impulse from our PF values were assessed with one-way ANOVAs with repeated measures for time. From the 30 training sessions PF, PA and impulse values were averaged over three consecutive visits to produce ten separate levels of time for analysis. Changes to kilocalorie, protein, Ca^{+2} intakes over time were each compared with one-way ANOVAs. PT and TTPT values per velocity were each analyzed with 2(leg) x 2(time) ANOVAs, with repeated measures for leg and time. PINP and CTT were each examined with paired t-tests. BMD and BMC values per skeletal site were each analyzed with 2(leg) x 2(time) ANCOVAs, with repeated measures for leg and time, and scan areas as covariates. If our analyses produced an interaction, Scheffe's post-hoc identified the source of the difference. An $\alpha = 0.05$ denoted significance for all analyses.

Results

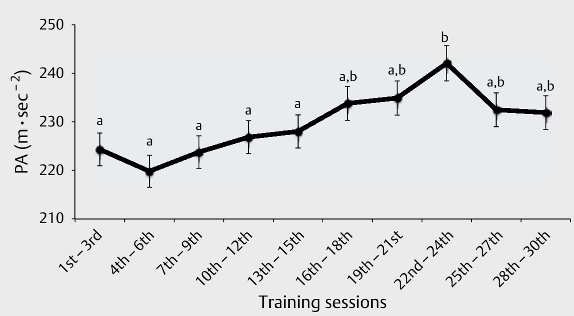
There were no injuries and subjects finished all 30 training sessions (100 % compliance). All ANOVA assumptions were met and Z-scores identified no outliers. Kilocalorie, protein and Ca^{+2} results appear in ▶ **Table 1**; there were non-significant changes over time. Per IET repetition, one impact force and impulse were produced. For each

▶ **Table 1** Subjects' kilocalorie, protein and calcium intakes (mean ± sd).

	First 3-day reporting period	Second 3-day reporting period	Third 3-day reporting period
kilocalorie (kcals· day^{-1})	2251 ± 950	1916 ± 472	1920 ± 641
protein (g· day^{-1})	92.7 ± 50.8	82.9 ± 39.7	96.8 ± 57.9
calcium (mg· day^{-1})	786 ± 568	588 ± 321	702 ± 468

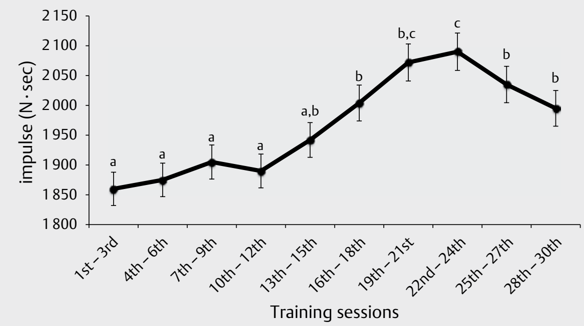


▶ **Fig. 6** Mean knee extension (mean ± sd, in Nm) PF results. Values with different letter superscripts denote significant ($p < 0.05$) inter-training session changes. Time points with two letter superscripts mean that measurement is statistically similar to other values that possess either superscript.

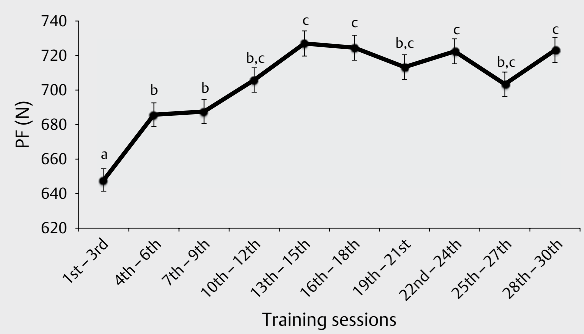


▶ **Fig. 7** Mean knee extension (mean ± sd, in m. sec-2) PA results. Values with different letter superscripts denote significant ($p < 0.05$) inter-training session changes. Time points with two letter superscripts mean that measurement is statistically similar to other values that possess either superscript.

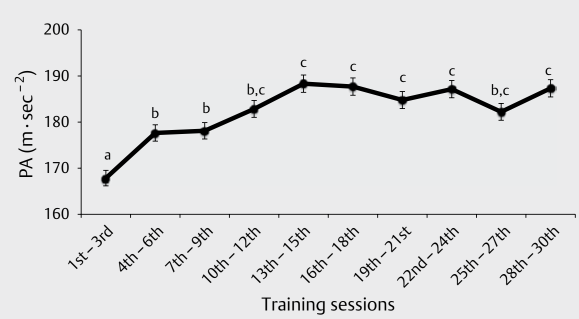
60-s set, subjects averaged (mean ± sem) 125.8 ± 29, 137.0 ± 32 and 115.4 ± 25 impact forces and impulses for the knee extension, hip extension and seated calf press, respectively, or roughly two per second of exercise. Over the 30 training sessions they gradually did more repetitions per set, which increased the rate and number of impact loads and impulses. ▶ **Fig. 6–14** depict changes to PF, PA and the impulse from the PF value per exercise, over our subject's 30 training sessions. Our one-way ANOVA results yielded significant changes for each figure. PF, PA and impulse increases attest



▶ **Fig. 8** Mean knee extension (mean ± sd, in N. sec) impulse results. Values with different letter superscripts denote significant ($p < 0.05$) inter-training session changes. Time points with two letter superscripts mean that measurement is statistically similar to other values that possess either superscript.

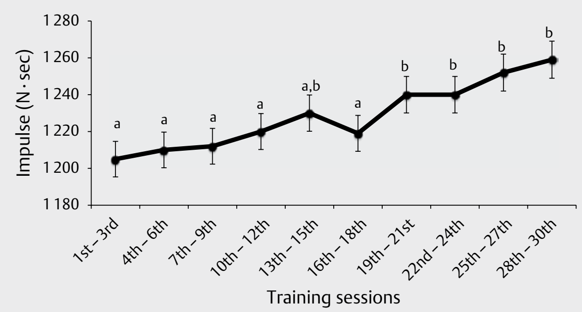


▶ **Fig. 9** Mean hip extension (mean ± sd, in Nm) PF results. Values with different letter superscripts denote significant ($p < 0.05$) inter-training session changes. Time points with two letter superscripts mean that measurement is statistically similar to other values that possess either superscript.



▶ **Fig. 10** Mean hip extension (mean ± sd, in m. sec-2) PA results. Values with different letter superscripts denote significant ($p < 0.05$) inter-training session changes. Time points with two letter superscripts mean that measurement is statistically similar to other values that possess either superscript.

to the progression and effort exerted by our subjects over the 30 training sessions. For ▶ **Fig. 6–14**, letter superscripts are used to identify changes per performance measure over time. Different let-



► **Fig. 11** Mean hip extension (mean ± sd, in N. sec) impulse results. Values with different letter superscripts denote significant (p < 0.05) inter-training session changes. Time points with two letter superscripts mean that measurement is statistically similar to other values that possess either superscript.

► **Fig. 12** Mean seated calf press (mean ± sd, in Nm) PF results. Values with different letter superscripts denote significant (p < 0.05) inter-training session changes. Time points with two letter superscripts mean that measurement is statistically similar to other values that possess either superscript.

► **Fig. 13** Mean seated calf press (mean ± sd, in m. sec-2) PA results. Values with different letter superscripts denote significant (p < 0.05) inter-training session changes. Time points with two letter superscripts mean that measurement is statistically similar to other values that possess either superscript.

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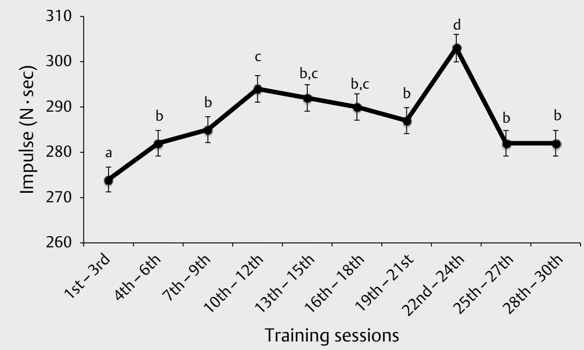


► **Fig. 14** Mean seated calf press (mean ± sd, in N. sec) impulse results. Values with different letter superscripts denote significant (p < 0.05) inter-training session changes. Time points with two letter superscripts mean that measurement is statistically similar to other values that possess either superscript.

Per velocity, ankle extensor PT data (► **Table 2**) produced two-way interactions (p = 0.02-0.03). Post-hoc analyses revealed left ankle extensor post-test values were significantly higher and were the source of each two-way interaction. Pre-post changes to ankle extensor PT values saw large (+ 18-21 %) left leg increases per angular velocity, while right leg PT data had non-significant (+ 5-7 %) changes. There was a two-way interaction for knee extensor PT at 0 rad· sec^{-1}. Post-hoc analyses revealed left knee extensor post-test values were significantly higher and the source of the two-way interaction. Pre-post changes to knee extensor PT at 0 rad· sec^{-1} were larger for the left (+ 11 %), as compared to the right leg (+ 3.6 %). The greater occurrence of two-way interactions for ankle extensor PT results, versus those for the knee extensors, is due their lower data variability, as evidenced by sd values in ► **Table 2**. Knee extensor TTPT at 4.86 rad· sec^{-1} elicited a non-significant trend (p = 0.10), with lower left leg values at post-testing.

PINP and CTT results are shown in ► **Table 3**. Higher, yet non-significant, post-test PINP increases occurred. Yet CTT analysis produced a significant (p = 0.03) decline in values over time. Results imply 30 IET sessions significantly suppressed bone resorption. BMC and BMD values appear in ► **Table 4**, **5**, respectively. Calcaneal BMC and BMD analyses each yielded significant (p = 0.04) two-way interactions. Post-hoc analysis revealed significant BMC (+ 29 %) and BMD (+ 33 %) accretion to the left leg's calcaneus, while the right calcaneus incurred losses. ► **Fig. 15**, **16** show trend lines, with substantial variability, for subject's left calcaneal BMC and BMD changes over time. ► **Fig. 15**, **16** variability were minimized when the data were analyzed with our covariate. There were no other significant BMC or BMD changes.

Discussion

There were significant improvements to our calcaneal and bone resorption variables, as well as to several PT indices. Our IET sessions created high PF, PA and impulse values that rose significantly over time. This was combined with an increase in the number of repetitions over the 30 sessions, and our study imparted unique mechan-

▶ **Table 2** Strength data (mean ± sem).

ankle extensor PT (Nm)	**Left leg**		**Right leg**	
	pre	**post**	**pre**	**post**
0 rad· sec⁻¹	110.5 ± 28	133.7 ± 27 *	120.6 ± 31	129.3 ± 31
1.62 rad· sec⁻¹	63.0 ± 16	75.0 ± 12 *	67.6 ± 16	71.3 ± 16
4.86 rad· sec⁻¹	45.8 ± 9	53.9 ± 9 *	47.3 ± 9	50.4 ± 9
ankle extensor TTPT (s)	**Left leg**		**Right leg**	
	pre	**post**	**pre**	**post**
0 rad· sec⁻¹	2.89 ± 1.48	2.86 ± 1.33	2.93 ± 1.69	2.82 ± 1.37
1.62 rad· sec⁻¹	0.21 ± 0.04	0.21 ± 0.04	0.25 ± 0.14	0.21 ± 0.04
4.86 rad· sec⁻¹	0.20 ± 0.14	0.19 ± 0.11	0.18 ± 0.07	0.17 ± 0.11
knee extensor PT (Nm)	**Left leg**		**Right leg**	
	pre	**post**	**pre**	**post**
0 rad· sec⁻¹	183.1 ± 63	203.7 ± 61 *	185.5 ± 81	192.3 ± 88
1.62 rad· sec⁻¹	144.6 ± 47	143.2 ± 40	146.6 ± 56	146.9 ± 59
4.86 rad· sec⁻¹	100.2 ± 32	102.6 ± 32	99.1 ± 36	104.7 ± 38
knee extensor TTPT (s)	**Left leg**		**Right leg**	
	pre	**post**	**pre**	**post**
0 rad· sec⁻¹	2.06 ± 0.72	2.35 ± 0.87	2.03 ± 0.90	2.04 ± 1.19
1.62 rad· sec⁻¹	0.37 ± 0.07	0.39 ± 0.11	0.37 ± 0.14	0.33 ± 0.07
4.86 rad· sec⁻¹	0.19 ± 0.07	0.18 ± 0.07	0.18 ± 0.07	0.19 ± 0.07

* : source of the 2 (leg) x 2 (time) interaction

▶ **Table 3** Blood marker (mean ± sem) results.

Marker	**pre-test**	**post-test**
Procollagen type I intact terminal propeptide (μg· L⁻¹)	50.6 ± 24.2	56.2 ± 20.6
C-terminal telopeptides of type I collagen (pg· ml⁻¹)	386.2 ± 97	336.9 ± 86 *

* : significant (p < 0.05) decline versus corresponding pre-test value

▶ **Table 4** Bone mineral content (BMC; in grams) values expressed as mean ± sd.

VARIABLE	**LEG**	**VALUES**	
		Pre	**Post**
Calcaneus	Left	4.5 ± 1.9	5.8 ± 3.2 *
	Right	5.0 ± 1.6	4.5 ± 2.2
Distal Tibia	Left	29.7 ± 5.2	29.9 ± 5.5
	Right	27.9 ± 8.4	29.7 ± 4.8
Distal Femur	Left	69.6 ± 13.2	70.6 ± 12.3
	Right	67.1 ± 13.6	70.3 ± 12.3
Proximal Tibia	Left	48.2 ± 10.4	48.8 ± 10.4
	Right	45.6 ± 10.5	48.5 ± 13.4
Femoral Neck	Left	8.9 ± 2.7	9.1 ± 2.6
	Right	7.8 ± 1.7	8.6 ± 2.1
Trochanter	Left	9.0 ± 2.1	8.1 ± 2.9
	Right	8.5 ± 1.6	8.2 ± 1.7
Inter-Trochanter	Left	22.4 ± 4.8	22.0 ± 5.0
	Right	21.8 ± 4.4	21.5 ± 4.5
Total (Hip)	Left	40.3 ± 8.8	39.3 ± 8.5
	Right	39.7 ± 10.0	38.4 ± 7.9
Wards	Left	1.0 ± 0.2	1.0 ± 0.3
	Right	1.0 ± 0.3	1.0 ± 0.3

* : source of the significant 2 (leg) x 2 (time) interaction (p < 0.05)

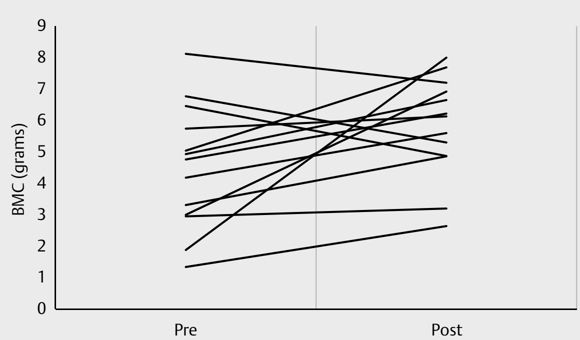
ical loading stimuli, which is perhaps why some dependent variables exhibited significant gains. In contrast various exercise/therapeutic modalities were examined for their impact on BMC and BMD, but many appear to lack at least one mechanical loading feature. For instance, chronic high-speed activity and whole body vibration do not impart sufficient magnitudes of force, which may limit bone growth [1, 21, 28, 44]. Conversely, the rate and frequency of mechanical stimuli is compromised by heavy loads used with resistive exercise [15, 16, 58]. Yet our data produced a dichotomy, as IET sessions yielded little change to some dependent variables, while others saw significant benefit. Based on the variables that improved, our hypothesis was partially affirmed. Pre-post increases to left calcaneal BMC and BMD far exceed gains seen previously and may be due to a significant decline in bone resorption [2, 19, 58]. It is important to explain why our BMC and BMD results 1): yielded greater gains than other studies, and 2): were confined to the calcaneus.

Chronic resistance exercise (e. g. 3–48 months) with heavy (70-90 % 1RM) loads 2-5 days per week yielded small (+ 1-3 %) BMC and BMD gains [15, 16, 58]. Such protocols have not always led to osteogenesis; in cases when it merely abated bone losses, it was deemed useful [19, 58]. Inclusion of power exercises to chronic (5-50 month) strength training programs usually elicited greater (+ 0-13.5 %) BMC and BMD gains [4, 20, 25, 53]. This led some to imply power training, with its high movement rates and impact forces, was better for osteogenesis [14, 16, 24, 33]. A combined 26-week aerobic and resistive exercise intervention produced modest (+ 1.7-2.5 %) BMD gains in female cancer survivors [2]. Impact forces from tennis (averaged 14.3 years of play) led to dominant arm muscle volume (+ 9.7 %) and BMC (+ 13.5 %) gains versus the non-dominant arm

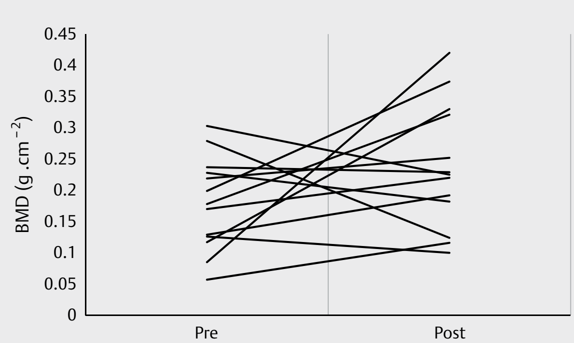
▶ **Table 5** Bone mineral density (BMD; in g· cm^{-2}) values expressed as mean ± sd.

VARIABLE	LEG	VALUES	
		Pre	Post
Calcaneus	Left	0.18 ± 0.06	0.24 ± 0.11 *
	Right	0.20 ± 0.06	0.18 ± 0.09
Distal Tibia	Left	0.98 ± 0.27	1.07 ± 0.11
	Right	0.97 ± 0.27	1.03 ± 0.18
Distal Femur	Left	1.22 ± 0.18	1.19 ± 0.11
	Right	1.16 ± 0.18	1.18 ± 0.18
Proximal Tibia	Left	1.02 ± 0.11	1.01 ± 0.11
	Right	0.99 ± 0.11	1.01 ± 0.18
Femoral Neck	Left	1.01 ± 0.18	0.99 ± 0.18
	Right	0.99 ± 0.18	0.99 ± 0.11
Trochanter	Left	0.82 ± 0.09	0.81 ± 0.11
	Right	0.81 ± 0.09	0.80 ± 0.09
Inter-Trochanter	Left	1.27 ± 0.18	1.27 ± 0.18
	Right	1.27 ± 0.11	1.24 ± 0.11
Total (Hip)	Left	1.08 ± 0.11	1.07 ± 0.11
	Right	1.07 ± 0.11	1.06 ± 0.11
Wards	Left	0.85 ± 0.18	0.84 ± 0.18
	Right	0.83 ± 0.18	0.85 ± 0.18

* : source of the significant 2 (leg) x 2 (time) interaction ($p < 0.05$)



▶ **Fig. 15** Trend line display of subjects' left calcaneal BMC values (in grams).



▶ **Fig. 16** Trend line display of subjects' left calcaneal BMD values (in grams. cm-2).

[18]. Exercise performed using disuse models showed that a year of electrical stimulation in paraplegics led to significant leg muscle girth (+ 35.5 %) and BMD (+ 7 %) gains Yet a combined flywheel exercise-bisphosphonate treatment only partially abated leg muscle and bone loss during 90 days of bed rest [23, 42].

While strength training preserves bone, it is a difficult means by which to do so, as years of exercise with high force exertion provide, at best, modest BMD gains [14–16, 20, 58]. The likely cause for our IET intervention to yield better calcaneal results is the manner in which each exercise modality imparts mechanical loading stimuli. Resistance exercise imparts strain magnitudes that routinely exceed osteogenic thresholds, but, as its repetitions occur slowly, low strain rates and frequencies may limit BMD gains [14–16, 58]. In contrast our sled, load was light, which allowed IET repetitions to attain high PF, PA and impulse values that in turn may have led to gains in strength, BMC and BMD [14, 17, 28]. High PF and impulse values suggest despite a light load, the IET offers a potent mechanical loading stimulus that, at least for the calcaneus, elicits bone growth [14]. Our results imply it is perhaps best for PF, PA and impulse values to all be high; to neglect one may limit the merits of exercise [14, 17, 28, 58].

Similar to standard resistance exercise, animal data saw inverse relationships between the magnitude and frequency of strain imparted to bones [14]. In rodents, high magnitudes led to concurrent declines in frequency; conversely, as magnitude declined the frequency needed to evoke osteogenesis increased [14, 29, 48]. In active adults, strain magnitudes seen with many forms of exercise are relatively low [14]. In contrast, at repetition frequencies of roughly two per second, as well as with high PF and impulse values, the IET may have imparted mechanical load stimuli with both high magnitudes and frequencies. In turn, this may have led to large BMC and BMD gains to the calcaneus, if not other bones examined in the current study [15, 16, 58].

Unlike resistance exercise, BMD results from mechanical loading stimuli that did not impart sufficient magnitudes of force also yielded fewer gains than our calcaneal results [1, 21, 28, 44, 54]. They include chronic interventions in which subjects received whole body vibration [21, 44] or wore an accelerometer as they performed high-speed activity [1, 28, 54]. Whole body vibration's impact on BMD is unclear and likely the result of multiple factors [21, 44]. In contrast impact loading from high-speed physical activity yielded small (+ 1.1-1.9 %) but significant BMD gains [28]. A correlation occurred between impact frequency and calcaneal growth [17, 28]. Since those studies did not report PF or impulse data, modest BMD changes were most likely due to the lower forces exerted [1, 28, 54]. Yet to affirm that assertion, more data from human subjects is needed.

There does not appear to be a study that approaches the calcaneal accretion of our investigation. Yet our results are perhaps most like those from a high-speed, light-load intervention administered to postmenopausal women [25]. Over 42 days, subjects trained twice per week with a weighted vest; their BMD changes were compared to those of untrained controls. Similar to our study, analysis of multiple BMD sites only produced one anatomical location that significantly improved, as pelvic BMD rose 1.6 % from training while controls incurred a 1 % loss to that variable [25]. Compared to our study, Hamaguchi et al. had an exercise volume of only three repetitions per set administered over a shorter time period [25]. In contrast, our subjects performed roughly two repetitions per second for each 60-s set. Also over the 30 sessions our subjects gradually did more repetitions per set, which raised the rate and number of impact loads and impulses. It also enhanced weight sled acceleration, as seen by the significant PA rise per current study exercise. Despite somewhat similar mechanical loading paradigms, as perhaps both may evoke high PF, PA and impulse values, there was a vast difference in the exercise volume between studies. It is of interest to speculate on the degree of BMD accretion by Hamaguchi et al. had it entailed a similar training volume as our study.

The calcaneus has the most trabecular bone (> 95 %) of the human body [41]. Since it is also a weight-bearing bone, it is quite responsive to mechanical stimuli [41]. In turn, the degree to which our most highly responsive subjects adapted to our novel exercise stimulus contributed to our left calcaneal BMC and BMD gains shown in ▶ **Table 4**, **5**, and the considerable variability shown in ▶ **Fig. 15**, **16**. Our BMC and BMD gains were confined to the calcaneus, our most distal bone examined. ▶ **Table 4**, **5** depict a curious anatomical outcome, as greater inter-leg and -time differences occurred at more distal bone segments. Precedent exists for greater growth at distal locations [30]. Bone formation was assessed at multiple sites in adult rats. By applying similar loads significantly higher strains, and more growth, occurred at distal sites as compared to the mid-diaphysis [30]. In turn, the mid-diaphysis had higher strains and bone growth than proximal sites [30]. With 5 N loads, distal sites received roughly 50 % and 130 % more strain than its medial and proximal segments, respectively [30]. Higher loads evoked linear strain increases, and with 20 N the distal sites received roughly 45 % and 205 % more strain than its medial and proximal segments, respectively [30]. Despite higher thresholds at distal sites, exceeding those thresholds is easier, where a given load induces more strain. Similar outcomes also occurred to young rats [40]. Yet since we did not obtain strain data, we cannot confirm left calcaneal BMC and BMD gains were the result of relatively greater strains at more distal anatomical sites.

Our low calcaneal values were likely due to the body posture used for scans. Calcaneal BMC and BMD values are typically derived from total-body DEXA scans, where persons lie supine as an overhead scanner forms a densitometry image, and afterwards region of interest software locates the calcaneus. Yet from an overhead view and supine posture much of the calcaneus bone is obscured by other bones, thus BMC and BMD values derived in this manner may be inflated. In contrast, our scans isolated the medial lower leg surface, which allowed us to assess the largest surface of the calcaneus unobstructed by other bones. Thus we believe our calcaneal BMC and BMD values are appropriate given the subject's body posture. Yet a recent study, with calcaneal BMD measurements carried out in a similar body posture, produced far higher calcaneal values in spinal cord-injured subjects [41]. Differences in calcaneal BMD between the current and Peppler studies were likely due to disparities in the densitometers and gender composition. With adult subjects, Peppler et al. used a densitometer intended for pediatric populations [41]. Since adults usually have higher BMD values than children, when the former are scanned on pediatric densitometers and/or software they may yield inflated results. In contrast our densitometer was best suited for adults, which was the sample assessed in our study. In addition, our subjects were mostly female (2 men, 11 women), yet Peppler et al. do not state the genders of their subjects [41]. Since men usually have higher BMD values than women, this may be why Peppler et al. produced higher calcaneal outcomes [41].

Since the IET does not require gravity to operate, and has small mass and power features, it could serve as in-flight hardware for astronauts, a disuse model for whom greater musculoskeletal losses occur with longer exposures to microgravity. In-flight total body BMD losses occur at rates of 1-3 % per month [27, 29, 46, 47], yet longer unloading periods show the calcaneus incurs higher rates (~5 % per month) of loss [13, 51]. Thus calcaneal losses must be a priority addressed by in-flight exercise. Heightened resorption in microgravity accelerates bone loss [38, 46, 47]. Potential in-flight treatments to limit resorption include bisphosphonate therapy. Yet bisphosphonates have numerous side effects (hypocalcemia, hyperthermia, fatigue, kidney damage) that may be exacerbated in-flight [35, 50]. In contrast, our results include a suppression of bone resorption.

In-flight resistive exercise hardware include the Advanced Resistive Exercise Device (ARED) and flywheel ergometers. Each imparts high loads. The ARED abated bone loss but is not practical for Mars missions due to its high mass and power needs [47]. An early flywheel ergometry paper touted their ability to improve muscle mass and strength, yet was less enthusiastic about their impact on bone [5]. Subsequent research affirmed this concern, as large flywheels may slow strain rates and frequencies that negated bone growth [8, 9]. Flywheel ergometry had little success at strength and bone loss mitigation during long-term unloading, yet with concurrent albuterol therapy there was significant benefit [9, 10]. Given our results, which included suppression of bone resorption and a unique mechanical loading stimulus that led to strength gains and calcaneal accretion, the IET warrants further inquiry. Since the IET operates independent of gravity and its design conforms to in-flight requirements, future research should assess musculoskeletal changes from chronic exercise in a space flight model, such as human bed rest subjects.

In addition to its potential to abate in-flight musculoskeletal losses, as our study used ambulatory subjects, the IET could be used in terrestrial models with subjects that have similar impairments [15, 16]. These include female military recruits, who incur higher rates of lower body stress fractures from basic training than their male counterparts [32]. Since it uses lighter loads than standard resistive exercise, the IET may also benefit disuse models for whom heavier loads are impractical. Our results, which include significant strength and calcaneus improvements in ~ 70 days with light loads, suggest continued research with the IET is warranted, both with simulated space flight and terrestrial models.

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Conflict of Interest

The authors declare no conflict of interest.

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