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Musculoskeletal Outcomes from Chronic High-Speed High-Impact Resistive Exercise

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Abstract

Subjects (n=13) did 30 workouts with their left leg on an Inertial Exercise Trainer (IET), while their right leg served as an untreated control. Before and after the 30 workouts, they underwent isokinetic strength tests (knee and ankle extensors of both legs) whose peak torque (PT), time to PT (TTPT), and rate of torque development (RTD) values were each analyzed with 2(leg)×2(time)×3(velocity) analysis of variances (ANOVAs), with repeated measures per independent variable. Peak force (PF) and total work (TW) data were measured from each IET workout, and they represent time course strength changes produced by our exercise intervention. PF and TW values for the three IET exercises that comprised each workout were each analyzed with one-way ANOVAs with time as the independent variable. Results included significant ankle and knee extensor PT increases, whereby the left leg achieved higher values at posttesting, but there were no significant TTPT changes and a time effect for ankle extensor RTD. Our data show that PF and TW each had significant increases over time, with the latter exhibiting greater gains over the 30-workout intervention. Our results imply that the IET yields strength gains over time comparable to standard resistive exercise hardware .

Keywords

Resistive exercise • countermeasures • Inertial Exercise Trainer

INTRODUCTION

Musculoskeletal changes to chronic exercise offer a temporal framework for which to anticipate strength improvements and/or attenuation of in-flight losses from exercise hardware and/or protocols. Temporal changes refer to the rate and magnitude of adaptations over time, which help formulate training strategies to limit in-flight strength losses and thereby optimize long-term musculoskeletal health for long-term exposure to microgravity (Fleck and Kraemer, 2014). Two 60-day bed rest studies assessed temporal adaptations to concurrent exercise countermeasures that sought to abate musculoskeletal losses (Kramer et al., 2017; Trappe et al., 2007). Those countermeasures included flywheel-based resistive exercise (Trappe et al., 2007) and high-intensity jump training (Kramer et al., 2017). Results showed that concurrent exercise reduced muscle mass and strength losses in those who received the experimental treatment as compared to bed-rested controls, yet neither countermeasure addressed bone losses, which is an important in- and postflight concern (Kramer et al, 2017; Trappe et al., 2007). However, a recent study with ambulatory subjects examined a 30-workout high-speed high-impact resistive exercise intervention on muscle and bone adaptations (Caruso et al., 2018). Subjects trained their left knee and ankle extensors on the high-speed high-impact device while the same muscle groups on their right legs served as untreated controls. Strength data obtained before and after the 30-workout intervention showed significant gains in left leg's knee and ankle extensor strength (Caruso et al., 2018). Yet, unlike the aforementioned bed rest studies, 30 workouts on the high-speed high-impulse device evoked large and significant gains in left leg's calcaneal bone mineral content (+29%) and density (+33%), as well as a significant decline in osteoclast activity (Caruso et al., 2018). Such results hold much promise, as the calcaneus incurs among the largest in-flight losses that are exacerbated by heightened osteoclast activity (Heer et al. 2005; LeBlanc et al., 2007).

The high-speed high-impact device, called an Inertial Exercise Trainer (IET; Impulse Technologies, Newnan, GA), has a mass sled that traverses its 1.9-m track parallel to the Earth's surface and is thus not impacted by gravitational forces. The high-speed nature of its repetitions is created by the IET's low-friction track in which the sled glides upon with little force exertion (Davison et al., 2010). The IET has low mass, area, power needs and is easy to stow and operate, allowing it to conform to in-flight hardware guidelines (Smith et al., 2014). Impact forces are incurred as the sled changes direction with each new repetition, which is also when the peak force (PF) for each repetition occurs. With

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2.0–2.5 repetitions done per second over 1-min sets, as well as an average PF of 900 N for one of its exercises, the IET is indeed a high-speed high-impact training device (Caruso et al., 2018). With a small mass added to its sled and rapid force exertion, its repetitions are inherently ballistic. Impulses (D force/D time) from each repetition impart far different mechanical loading stimuli than standard exercise hardware. Thus, the IET may yield temporal adaptations to strength-based variables unlike those seen previously which, to date, have not been examined. Figures 1 and 2 show the overhead and side view illustrations of the IET, respectively.

Studies that charted temporal strength changes used variables such as peak torque (PT) to assess improvements caused by exercise interventions (Caruso et al., 1997). PT is a muscle's maximal ability to exert force (Brown 2000). Despite differences in workout and test modalities, the use of PT to assess performance changes was extended to training studies whereby exercise occurred against heavy loads with standard resistive exercise equipment (Gentil et al., 2006). Due to the high-speed nature of IET repetitions, perhaps better variables to test performance changes from its chronic intervention are time to PT (TTPT) and rate of torque development (RTD), which are instantaneous variables often cited as key determinants of success in performance tasks where reaction time is crucial (Brown et al., 2005). Since IET repetitions occur at high rates of speed, TTPT and RTD changes may prove valuable to monitor.

Figure 1. Overhead illustration of the IET. IET, Inertial Exercise Trainer.

Understanding temporal changes is essential to aid in the development of successful exercise prescriptions. Chronic high-speed IET training may yield unique neuromuscular adaptations that also evoke improvements in PT, TTPT, and RTD values over time (Cormie et al., 2009). Our study quantifies adaptations to strength gains from a chronic training intervention, whereby PF and total work (TW) values from IET workouts are monitored over time, for their impact on PT, TTPT, and RTD changes measured by strength tests on an isokinetic dynamometer. We use IET workout data from the aforementioned investigation (Caruso et al., 2018) as part of our study's analyses. We hypothesize in healthy subjects, whereby one leg undergoes the IET intervention and the other serves as an untrained control, that their trained leg's adaptations over time will yield significant PT, TTPT, and RTD improvements from the IET intervention.

MATERIALS AND METHODS

Experimental Approach to the Problem

Subjects did 30 IET workouts with their left leg, at an average rate of one every 2.3 days, while their right leg served as an

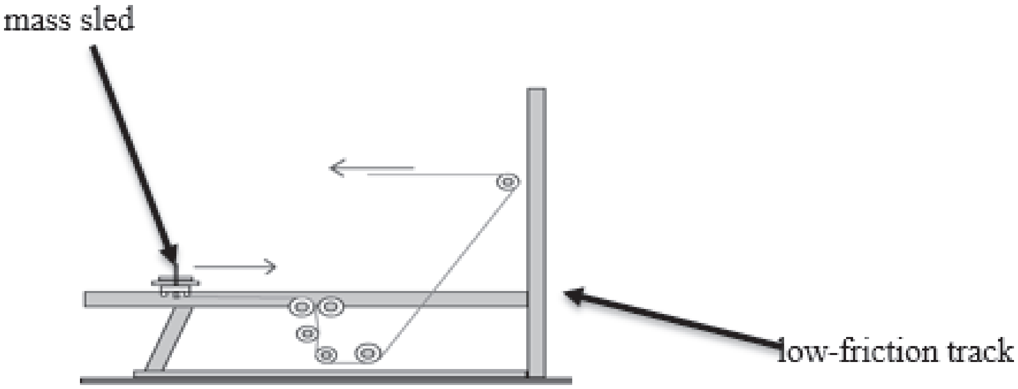

Figure 2. Side view illustration of the IET.IET, Inertial Exercise Trainer.

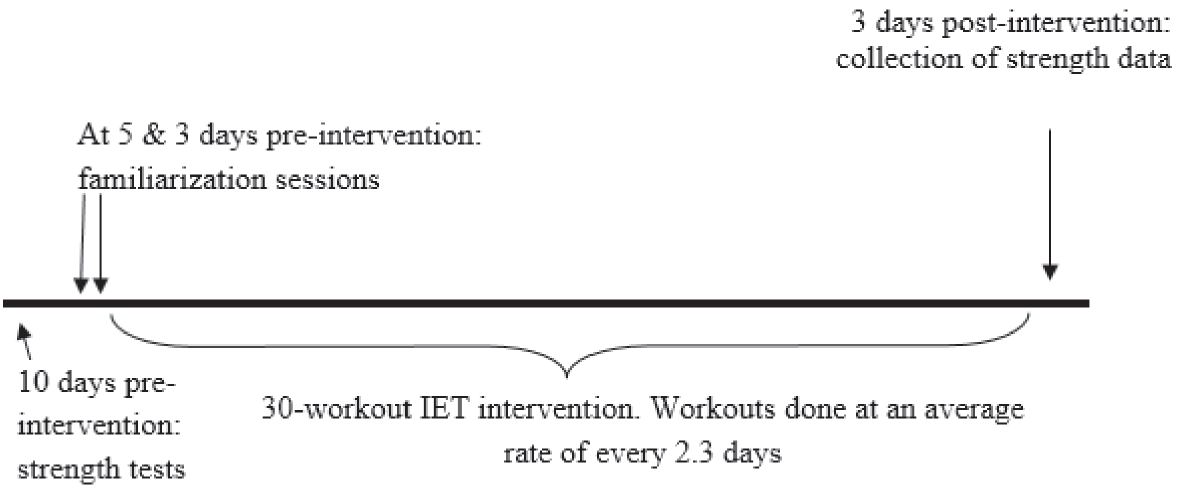

Figure 3. Timeline of subject's involvement (current study).

untreated control. The IET was instrumented with software that allowed real-time capture of data. Variables from IET workouts were recorded and examined for changes over time. Before and after the 30-workout intervention, subjects also underwent isokinetic strength tests, at three angular velocities, for the knee and ankle extensors of both legs, to provide PT and TTPT values. PT and TTPT changes in the left leg may be attributed to IET workouts. Per subject, Figure 3 depicts a timeline with an overview of their involvement.

Subjects

Before admittance into our study, the University of Louisville's Institutional Review Board approved all procedures. Subjects (mean ± standard error of the mean [SEM]: 29.4±5 years; two 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. Aside from the physical requirements of their normal daily activities, our subjects did not engage in exercise during their participation. Their body mass and body fat percentage were 69.2±3 kg and 26.9±0.20%, respectively. They were well versed in various forms of exercise, but none had prior experience with IET workouts. Thus, prior to the intervention, each subject did two familiarization sessions so repetitions were done correctly.

Familiarization sessions

Subjects practiced repetitions with their left leg for the following exercises: standing knee extension, standing hip extension, and seated calf press. Each was done with 3.4 kg of mass added to the 1.0 kg IET sled. Knee extension was done with a velcro cuff around their distal left shank. As the knee extended ~10–15°, the sled traveled rapidly to the end of the track. 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 accelerated the sled to the track's opposite end. These high-speed movements were repeated over successive repetitions until subjects were proficient in the exercise. Changes in sled direction created an impact force, which was high due to the sled's rate of movement (Davison et al., 2010). Per impact force, high PF and impulse (D force/D time) values were also generated. Figure 4a and b depicts the standing knee extension exercise.

With a velcro strap wrapped around the arch of subject's left foot, the standing hip extension exercise was done in a similar fashion. Figure 5a and b depicts hip extension repetitions. Unlike the knee and hip extension exercises, the seated calf press was 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 heads of subjects' left feet. Figure 6a and b depicts seated calf presses on the IET. Like the standing knee extension exercise, per standing hip extension and seated calf press repetition high PF and impulse (D force/D time) values were generated. The principal investigator was present to ensure that, by the end of familiarization sessions, subjects properly executed repetitions per exercise.

Workouts

All 30 workouts that comprised the IET intervention were carried out in the same manner. They commenced with a 5-min bilateral warm-up on a cycle ergometer (Ergotest, Stockholm,

Figure 4. (a, b) Knee extension exercise performed on the IET (current study). IET, Inertial Exercise Trainer.

Figure 5. (a, b) Hip extension exercise performed on the IET (current study). IET, Inertial Exercise Trainer.

Figures 6. (a, b) Seated calf press exercise performed on the IET (current study). IET, Inertial Exercise Trainer.

Sweden) against 1 kp of resistance at a self-selected velocity. Subjects then performed IET exercises in the following order with their left leg: standing knee extension, standing hip extension, and seated calf press. Per exercise, they did three 60-s sets separated by 90-s rests. They were instructed to exert maximal effort and were verbally encouraged during sets to perform repetitions as rapidly as possible as they maintained proper form. Our exercise protocol's rationale stems from the idea that osteogenic exercise should be nontraditional and/or nonsteady state in nature (Mittag et al., 2015; Yang et al., 2015, Yang et al., 2014). To evoke greater osteogenesis, we attempted to elicit high bone strains over short durations (Lanyon et al., 1986; Lanyon 1992; Nguyen et al., 2008). Three sets per exercise were done since bone strain stimuli reached a saturation point after only a few cycles (Lanyon et al., 1986; Lanyon 1992).

IET instrumentation entailed a calibrated TLL-2K load cell (Transducer Techniques, Temecula, CA) and position sensor (Model CX3-AP-1A, Automationdirect.com) anchored to the center of the track, directly below the path of the mass sled. Load cell and position sensor data were continuously sent to a DI-158U signal conditioner (DATAQ Instruments, Akron, OH) and assessed on separate channels at 4000 Hz. Our instrumentation methods provide reproducible data (Caruso et al., 2008). Workouts were 25 min in duration. Per set and exercise, we derived a PF and TW value, which represents instantaneous and cumulative measures of exercise performance, respectively. Increases to PF and TW values over the 30-workout intervention represent adaptations over time produced from training. Per exercise, PF and TW values were averaged and pooled across six consecutive time periods (for workouts 1–6, 7–12, 13–18, 19–24, 25–30), which allowed a comparative examination of each training variable's temporal changes.

Isokinetic strength testing

Left and right leg knee extensor strength tests, followed by those for the ankle extensors, occurred before and after the 30-workout intervention. Tests occurred at three (0, 1.62, and 4.86 rad./second) angular velocities. For each test, we aligned subject's knee or ankle joint with the dynamometer's (System 3 Biodex, Shirley, NY) axis of rotation and were held constant across test sessions. 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 repeated the paradigm at 1.62 rad./second, and then 4.86 rad./second over a 90° range of motion. 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 that of the knee extensors. PT and TTPT values, from maximal effort contractions, were obtained per velocity. We also calculated RTD as the D torque/D time ratio.

Statistical Analyses

Our sample size was based on a power analysis conducted prior to data collection. Ten subjects offered >90% power to detect a 15% change from our 30-workout intervention with a two-factor repeated-measures design with leg and time as within-subjects factors (Fritton et al. 2008). Thus, our sample (n=13) should exceed these power and change thresholds for our three-factor repeated-measures PT, TTPT, and RTD analyses. Our data were examined for compliance with analysis of variance (ANOVA) assumptions (normality, independence, equal variances). PF and TW values per exercise were examined with one-way ANOVAs from average values for the five time periods. Those five periods were as follows: workouts 1–6, workouts 7–12, workouts 13–18, workouts 19–24, and workouts 25–30. PT, TTPT, and RTD values were each analyzed with 2(leg) × 2(time) × 3(velocity) ANOVAs, with repeated measures for leg, time, and velocity. An alpha level of 0.05 denoted significance for all analyses. Tukey's HSD test identified the source of the differences.

RESULTS

TW results include significant temporal changes. Seated calf press TW values (mean ± SEM, in joules) for the five time periods were as follows: workouts 1–6 444,570±40,152, workouts 7–12 539,919±44,042, workouts 13–18 569,380±48,427, workouts 19–24 591,483±52,948, workouts 25–30 602,543±54,199. Post hoc analysis of seated calf press TW results was as follows: 25–30, 19–24>13–18>7–12>1–6. Standing hip extension TW values (mean ± SEM, in joules) for the five time periods were as follows: workouts 1–6 320,737±19,740, workouts 7–12 373,530±20,495, workouts 13–18 413,573±21,327, workouts 19–24 440,162±23,804, workouts 25–30 454,303±21,860. Post hoc analysis of standing hip extension TW results was as follows: 25–30>19–24>13–18>7–12>1–6. Standing knee extension TW values (mean ± SEM, in joules) for the five time periods were as follows: workouts 1–6 343,236±18,932, workouts 7–12 378,300±16,214, workouts 13–18 413,833±19,017, workouts 19–24 441,705±22,981, workouts 25–30 448,803±21,923. Post hoc analysis of standing knee extension TW results was as follows: 25–30, 19–24>13–18>7–12, 1–6.

PF results include significant changes over time, although its highest values occurred earlier in the intervention. Seated calf press PF values (mean ± SEM, in kilogram) for the five time periods were as follows: workouts 1–6 25.2±0.86, workouts 7–12 23.3±0.86, workouts 13–18 24.1±0.57, workouts 19–24 24.9±0.58, workouts 25–30 24.3±0.54. Post hoc analysis of seated calf press PF results was as follows: 19–24 > 25–30, 13–18, 7–12, 1–6. Standing hip extension PF values (mean ± SEM, in kg) for the five time periods were as follows: workouts 1–6 68.0±3.9, workouts 7–12 71.0±3.6, workouts 13–18 74.0±4.2, workouts 19–24 73.2±3.7, workouts 25–30 72.7±3.5. Post hoc analysis of standing hip extension PF results was as follows: 13–18>19–24, 25–30, 7–12>1–6. Standing knee extension PF values (mean ± SEM, in kilogram) for the five time periods were as follows: workouts 1–6 87.6±3.7, workouts 7–12 88.6±3.5, workouts 13–18 90.1±3.1, workouts 19–24 93.8±3.0, workouts 25–30 91.4±3.3. Post hoc analysis of standing knee extension TW results was as follows: 19–24>25–30, 13–18>7–12, 1–6.

PT, TTPT, and RTD results are summarized in Tables 1–6, with knee and ankle extensor data presented for the left (trained) and right (untrained) leg per time point and angular velocity examined. Despite the high speed nature of the IET, Table 1 only shows significant knee extensor PT increases at 0 rad./second. Post hoc analyses showed that left knee extensor PT posttest values were the interaction source. Pre–post percentage gains in knee extensor PT were higher for the left (+11%), than the right (+4), leg. Yet, Table 2 shows significant two-way ankle extensor PT gains per velocity examined. Left ankle extensor posttesting values were the source of each two-way interaction. Pre–post percentage ankle extensor PT increases were higher for the left, than the right, leg at 0 (+21% vs +7%), 1.62 (+19% vs +5%), and 4.86 (+18% vs +7%) rad./second. Tables 3 and 4 display nonsignificant TTPT changes for the knee and ankle extensors, respectively. TTPT data show more variability than PT values, which accounts for the lack of statistical significance. RTD results show nonsignificant knee extensor (Table 5) changes, while Table 6 shows ankle extensor data elicited a time effect (post-intervention>pre-intervention).

DISCUSSION

Our results include significant two-way ankle and knee extensor PT increases. With different modalities for workouts and strength tests, our time course changes suggest an IET intervention that evokes large increases in TW (+30–42%), but not PF (+7–9%) and yields significant gains in isokinetic PT, but not TTPT and RTD, over time. Our IET intervention averaged 10 weeks to complete 30 workouts. Some studies that also examined high-speed exercise employed training interventions of comparable durations. It is of interest to compare our results to those studies. A 10-week total body resistive exercise program evoked similar elbow flexor PT gains among men (+11.6%) and women (+11.8%) which concur with the magnitude of our study's knee extensor PT increases when tested at 0 rad./second (Gentil et al., 2016). Men were assigned to a strength, power, or a nonexercise group with no crossover for 10 weeks (Cormie et al., 2009). Strength subjects did back squats at 75–90% of 1RM loads, while the power group did jump squats at 0–30% of 1RM loads. There were comparable vertical jump (+17%) and sprint (+2%) gains after 10 weeks among the trained groups, yet strength-trained subjects had greater squat 1RM gains (+31.2%) than those who were power trained (+4.5%). Strength training enhanced

Table 1. Knee extensor PT (mean ± SEM in Nm) results.

Velocity (rad./second)	Left leg		Right leg	
	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
0	183.1±18.3	203.3±17.3[+]	185.5±23.3	192.3±24.8
1.62	144.6±13.2	143.2±10.9	146.6±15.5	146.9±16.8
4.86	100.2±8.8	102.6±9.0	99.1±9.9	104.7±11.4

[+] Source of a two-way (leg×time) interaction; greater ($p<0.05$) than the other treatment means for that velocity.
PT, peak torque; SEM, standard error of the mean.

Table 2. Ankle extensor PT (mean ± SEM in Nm) results.

Velocity (rad./second)	Left leg		Right leg	
	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
0	110.5±7.9	133.7±7.5[+]	120.6±9.0	129.3±9.4
1.62	63.0±5.0	75.0±4.4[+]	67.6±5.0	71.3±5.1
4.86	45.8±3.0	53.9±3.1[+]	47.3±3.2	50.4±2.7

+Source of a two-way (leg× time) interaction; greater ($p<0.05$) than the other treatment means for that velocity.
PT, peak torque; SEM, standard error of the mean.

Table 3. Knee extensor TTPT (mean ± SEM in seconds) results.

Velocity (rad./second)	Left leg		Right leg	
	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
0	2.06±0.20	2.35±0.24	2.03±0.25	2.04±0.33
1.62	0.37±0.02	0.39±0.03	0.37±0.04	0.33±0.02
4.86	0.19±0.02	0.18±0.02	0.18±0.02	0.19±0.02

SEM, standard error of the mean; TTPT, time to peak torque.

Table 4. Ankle extensor TTPT (mean ± SEM in seconds) results.

Velocity (rad./second)	Left leg		Right leg	
	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
0	2.34±0.22	2.82±0.38	2.93±0.47	2.49±0.30
1.62	0.21±0.01	0.21±0.01	0.25±0.04	0.21±0.01
4.86	0.20±0.04	0.19±0.03	0.18±0.02	0.17±0.03

SEM, standard error of the mean; TTPT, time to peak torque.

Table 5. Knee extensor RTD (mean ± SEM in Nm/second) results.

Velocity (rad $\cdot$ sec^{-1})	Left Leg		Right Leg	
	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
0	99.3±12.0	84.6±11.3	109.1±17.1	109.1±19.5
1.62	407.5±37.3	343.9±41.4	446.4±56.8	400.9±52.7
4.86	608.5±69.1	538.9±58.9	664.0±96.1	581.5±114.2

RTD, rate of torque development; SEM, standard error of the mean.

Table 6. Ankle extensor RTD (mean ± SEM in Nm/second) results.

Velocity (rad./second)	Left leg		Right leg	
	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
0	49.3±7.3	79.5±24.7*	57.3±8.8	63.4±8.1*
1.62	325.1±31.0	373.0±29.4*	335.4±33.8	348.7±25.5*
4.86	276.1±35.9	365.0±60.7*	277.5±29.7	357.5±58.6*

*Post-intervention > Pre-intervention
RTD, rate of torque development; SEM, standard error of the mean.

force at multiple test velocities, while the power intervention led to similar gains in dynamic, but not isometric, force. Since EMG changes occurred to the power-trained group, it was concluded that the optimization of the stretch-shortening cycle may have enhanced their performance (Cormie et al., 2009).

In addition to the ballistic high-speed activity inherent to IET repetitions, such workouts also generate considerable eccentric muscle forces to maintain proper form. Like our study, prior research examined the ability of resistive exercise paradigms to evoke changes over time from ballistic and/or eccentric activity (Balshaw et al., 2016; Barrué-Belou et al., 2016). The effects of ballistic training were compared to other groups that received either a sustained training or nonexercise treatment over 12 weeks with no crossover (Balshaw et al., 2016). Both training groups exercised 3 days/week with four sets of 10 isometric knee extensor repetitions. Ballistic training increased PT (+17–34%), via increased neural drive (+17–28%), over all time points examined. In contrast, sustained training only improved PT (+0–23%) over the latter phase of test contractions. Ballistic training led to greater gains and, given the lesser demands of this modality, was deemed to aid muscle function and performance (Balshaw et al., 2016).

The effects of an 8-week submaximal eccentric ankle extensor protocol were examined in participants either trained 2 days/week at 0.35 rad/s, or served as untrained controls with no crossover (Barrué-Belou et al., 2016). Training loads were adjusted every 2 weeks to maintain a 75% maximum of eccentric torque for workouts. After 8 weeks, muscle activation (+23–29%) and force measurements (+18–21%) rose significantly in the eccentrically trained group. Results suggest that force increases produced by training were at least in part due to enhanced neural drive (Barrué-Belou et al., 2016). The magnitude of PT gains from ballistic and eccentric training studies concurred with the improvements in ankle extensor PT seen with our study's intervention (Balshaw et al., 2016; Barrué-Belou et al., 2016).

Like our study, a prior investigation monitored strength improvements over time, albeit its repetitions occurred at far slower rates (Caruso et al., 1997). Temporal knee extensor strength changes were assessed in subjects randomized to a concurrent oral albuterol or placebo treatment with no crossover (Caruso et al., 1997). Subjects trained on an isokinetic dynamometer, which imparted concentric and eccentric resistance, 2 days/week for 10 weeks at 0.79 rad./second. After 10 weeks, four dependent variables showed time effects (+8–18%) and six others had two-way interactions (+9–21%). The variables that exhibited time effects were concentric measures that elicited significant gains generally within the first 2–3 weeks of training. Five of the six variables with two-way interactions were eccentric and produced significant intergroup differences after 3 weeks of training. It was implied that relatively greater eccentric gains were from the higher forces exerted as muscles lengthen and/or faster rates of motor unit synchronization (Caruso et al., 1997). Despite differences in exercise modes and repetition rates, the magnitude of improvements for the knee extensor study is like those from our study (Caruso et al., 1997).

The current PT, TTPT, and RTD results produced small nonsignificant gains to the untrained leg over time, which implies a potential cross-education effect from the IET intervention. Yet, the magnitude of these gains is less than those reported in other papers, in which a comparable degree of improvement was achieved over a shorter time period (Green, Gabriel 2018; Hunter 2017). Nonetheless, our study's PT, TTPT, and RTD changes to the untrained leg may be the result of heightened central drive, which occurred in a prior study but has yet to be affirmed from IET workouts and thus warrant future inquiry (Green, Gabriel 2018). With our workouts geared toward bone growth, we achieved high strains over very short lengths of time, but to do so our absolute knee extensor range of motion per repetition was small. In contrast, a larger range of motion was used for knee extensor testing. This discrepancy represents a potential source of error for our knee extensor test results. Despite the discrepancy, our results include a significant two-way interaction for knee extensor PT at 0 rad./second, with left leg posttest values as the source of the differences. In contrast, knee extensor tests at 1.62 and 4.86 rad./second entailed dynamic movement, and discrepancies in the range of motion for knee extensor training and testing are possible reasons for those dependent variables that did not reach statistical significance. It is also of interest that ankle extensor ranges of motion for training and testing were similar, and analyses of test data for that muscle group produced two-way interactions for each of velocity examined.

Our IET intervention produced disparate results, as strength tests showed more benefit to ankle, as compared to knee, extensors, and significant improvements in PT, but less for TTPT and RTD. In similar fashion, IET workouts yielded relatively greater TW gains over time than PF for each exercise. It is important to explain possible reasons for these outcomes, as they may impact IET future training prescriptions. Aside from differences in the range of motion for testing the knee and ankle extensors, as well as inherent differences in PF and TW measurements, whereby the former is an instantaneous, and the latter a comprehensive, index of workout performance, there are other factors that account for our disparate results. In particular, the length of the Achilles tendon impacts the level of series elastic element activity from successive high-speed repetitions that likely has a major influence on ankle extensor strength test performance (Hunter et al., 2015).

Our IET workouts sought to provide an osteogenic benefit, for which nontraditional and/or nonsteady state forms of activity composed of high bone strains applied briefly over few loading cycles are recommended (Lanyon et al., 1986; Lanyon 1992; Mittag et al., 2015; Nguyen et al., 2008; Yang et al., 2015, Yang et al., 2014). Unloading-induced skeletal losses are highest in areas with weight-bearing responsibility and large amounts of trabecular bone, such as the calcaneus (Rittweger et al., 2009). Astronauts on Skylab 3 (59 days) and 4 (84 days) had significant calcaneal bone mineral density (BMD) losses that ranged from 4.5% to 8% and also produced large increases in bone resorption, as did many longer flights (Leblanc et al., 2007). Cosmonauts incurred calcaneal BMD losses that varied from 1% to 20% for missions of 75–184 days (Leblanc et al., 2007). Seventeen-week bed rest studies showed that the highest (9–10%) density losses in humans were to the calcaneus (Le Blanc et al., 2002; Shackelford et al., 2004). Since bones adapt to mechanical stimuli, treatments to abate to in-flight losses should include large muscle forces (Rittweger et al., 2010). Some think that skeletal remodeling is the sum total of muscular force exertion (Schoenau et al., 2002; Rittweger et al., 2000; Rubin & Lanyon 1987). The largest strains are produced by muscle forces (Schiessl et al., 1998). Given the results of the recent ambulatory study (Caruso et al., 2018), the IET holds considerable promise as an in-flight countermeasure to musculoskeletal losses. Our hypothesis was partially affirmed as IET workouts yielded significant gains in PT, but not TTPT and RTD, over time. The current results may aid in the development of in-flight protocols with the IET, as the knee and ankle extensors incur significant strength losses in microgravity (Fitts et al., 2000; Trappe et al., 2009). Since both muscle groups typically maintain posture against Earth's gravity, their adaptation to space flight sees losses in PF and TW (Fitts et al., 2000).

Vast musculoskeletal losses impair in-flight procedural tasks, mission goals, and astronaut health upon their return to Earth (Baldwin et al., 1996; Fitts et al., 2000). Similar changes occur to ground-based analogs. The knee and ankle extensors incur among the largest losses (Belavy et al., 2009; Riley et al., 2002; Widrick et al., 1998). A 14-day bed rest led to a 9% knee extensor torque loss (Bamman et al., 1998). A 30-day bed rest elicited knee extensor strength losses (-20%) like those of a 28-day space flight (Convertino et al., 1989). Simulated microgravity for 20–25 days evoked knee extensor torque deficits of 17–21% (Berg et al., 1991; Berg et al., 2007; Gogia et al., 1988; Schultze et al., 2002). Forty days of unloading (-17-22%) and 90 days of bed rest (-31–60%) led to larger knee extensor losses (Alkner et al., 2004; Caruso et al., 2004). Unloading for 14–17 days caused significant (9–18%) ankle extensor strength loss (Adams et al., 1994; Bamman et al., 1997; Widrick et al., 1998). Five weeks of bed rest evoked a 26% loss in ankle extensor strength (LeBlanc et al., 1988). After 40 days, research showed that ankle extensor strength losses were 25% less than preunloading values (LeBlanc et al., 1988). Resistance exercise, which imparts more intense mechanical loading stimuli than aerobic activity, preserved ankle extensor strength during short-term (14-21 days) unloading (Akima et al., 2003; Bamman et al., 1998; Schultze et al., 2002). Yet, despite in-flight aerobic and resistive exercise done 5 and 3 days/week, respectively, 6 months aboard the International Space Station still led to significant ankle extensor mass and strength losses and shifts to faster myosin isoforms to create a more fatiguable muscle (Trappe et al., 2009). It was concluded that hardware that offers a different mechanical loading stimulus was required for long-term manned space travel (Trappe et al., 2009).

An absence of in-flight mechanical loading not only adversely impacts musculoskeletal health and performance, but inevitably compromises other body systems. NASA goals of long-term manned space exploration cannot be met unless the issue of in-flight musculoskeletal and strength losses is addressed. Thus, exercise countermeasures to these adverse effects must be a priority. Given our results, whereby workouts produced time course gains in PF and TW that led to gains in PT at multiple angular velocities, the IET warrants continued inquiry. Future research on temporal adaptations to chronic IET interventions may include continued examination of some of our findings; they include 1) significant PT increases that coincided with relatively larger TW gains, as compared to those for PF achieved from workouts and 2) mechanisms that identify how cross-education effects are imparted by this unique exercise modality. Since the IET operates independent of gravity, and its design conforms to requirements for in-flight hardware, new research should assess musculoskeletal changes to chronic exercise in a space flight analog, such as human bed rest subjects (Smith et al., 2014).

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